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The Influence of Tactual Seat-motion Cues on Training and Performance in a Roll-axis Compensatory Tracking Task Setting

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May 2008

Interim Report for September 1980 to June 1985

Air Force Research Laboratory
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NOTICE

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14. ABSTRACT

A considerable body of knowledge exists regarding the influence of whole-body motion on the control behavior and task performance of a vehicle operator required to compensate for the effects of unexpected external disturbances. The research described was conducted to determine whether similar effects would be observed if the motion information were tactually displayed through the seat pan, rather than in a whole-body motion environment. The experiment was designed such that the transfer of training from a tactual dynamic seat display to a whole-body motion environment could also be evaluated. The experimental task required subjects to regulate for a random-appearing, roll-axis disturbance in a simulated vehicle having aircraft-like dynamics. A centrally located compensatory display, subtending about nine degrees, provided visual roll error information. Control inputs were made via a right side-arm isometric controller. The two-phase experiment included a training phase and a criterion phase. During training, subjects tracked under conditions of either visual information only, visual plus tactual seat cues, or visual in the one-to-one motion environment. Following training, all subjects were transitioned into the criterion whole-body motion environment. The data clearly demonstrate that a dynamic seat pan can effectively impart motion information, but the device—as used in this experiment—did not effectively train subjects to properly interpret and use the motion information available in the whole-body motion environment.

15. SUBJECT TERMS Manual Control, Motion Simulation, Dynamic Seat, Human Operator Describing Function

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CHAPTER 1

Introduction

1.1 Background

The use of dynamic tactual (i.e., tactile and kinesthetic) displays in tracking experiments is not new. Information has been displayed via vibrators, air jets, electrocutaneously, and mechanical kinesthetic stimulation (e.g., Craig and Sherrick, 1982; Hill, 1970; Loomis and Lederman, 1986; Sherrick and Cholewiak, 1986). As a rule, stimulation has been applied to relatively small areas at diverse body locations (typically involving the hands, arms, head, waist, chest, and back), and was motivated by a desire to find additional channels to communicate information to the operators of vehicles (Hill, 1970; Jagacinski et al., 1983; Schmid and Bekey, 1978). The experiment described in this report involves a tactual display, but contrasts with the work referenced above in a number of ways. This research was motivated by a desire to develop effective motion display devices capable of being located within the cockpits of flight simulators. The tactual display used in this case was a computer controlled dynamic seat pan; hence the information was displayed over a fairly broad area involving the buttocks and upper thighs (the "seat of the pants"). The thrust of this work was to investigate whether the information provided by the tactual display would be picked up and interpreted as useful motion information—i.e., whether the tactual display could effectively substitute for the whole-body motion environment. The second area of interest was whether human operators trained to perform a tracking task with the tactual information would transfer this skill to the whole-body motion environment.

There is a growing reliance on the use of flight simulators as a tool for both aircrew training and proficiency maintenance and for the design and evaluation of aircraft and aircraft subsystems (Federal Aviation Administration, 1980; Staples, 1978). This has prompted a general concern regarding the proper presentation, or display, of task relevant information (cues) to aircrew members in ground based simulators (Brown, 1978; Key et al., 1978; Levison and Baron, 1984; Staples, 1978). There are a number of task environments for which the proper display-of-motion information is essential in order that equivalent performance and control behavior be achieved (Howe et al., 1978; Hall, 1978; Hosman and van der Vaart, 1981; Oosterveld et al., 1980;

Shirley, 1968). The effective display-of-motion information in the limited environment of a ground based flight simulator is a particularly challenging problem. Oosterveld et al., (1980) have recommended that research programs be undertaken to investigate new techniques for inside-the-cockpit motion displays. The dynamic seat is one such inside-the-cockpit motion display which has recently become popular.

Originally developed under the trade name of "DYNASEAT" in 1962 (Bose et al., 1981), the display concept languished in this country until the mid-1970's when dynamic seats were installed in research simulators at NASA and Air Force facilities (Ashworth, 1976; Kron, 1975). Although a number of studies failed to detect any utility of dynamic seat cuing, the results of several investigations did suggest that the seats were capable of providing useful motion information (Ashworth et al., 1979; Ashworth et al., 1984; Parrish and Steinmetz, 1983; Puig et al., 1978). (Puig et al., (1978) summarize a number of studies with positive, equivocal, and negative outcomes.) Those studies which yielded positive results employed experimental scenarios wherein sustained, normal specific force cues were of primary interest. Researchers investigating the utility of dynamic seats for rotational cuing were unsuccessful in detecting any benefit (Showalter, 1978; Showalter and Parris, 1980). This is not surprising since the seats used in these earlier experiments were designed primarily to provide sustained normal g-loading cues, and were in fact called "g-seats" for this reason (Ashworth, 1976; Kron, 1975; Matthews and Martin, 1978).

It has been suggested that by better tuning the motion display devices to the characteristics of the perceptual channels serving the pickup of motion information, the efficiency of motion displays in flight simulators could be enhanced (Oosterveld et al., 1980; Young et al., 1973). Young (1982) has argued that the higher frequency response of the sensors serving the tactual modality would be ideal for signaling rapid changes in acceleration (i.e., acceleration "onset").

A dynamic seat specifically designed to display "onset" as well as sustained motion information (Albery et al., 1978) became available to support this research in 1980. The principal advantage of this new device over earlier "g-seats" lay in its frequency response. While bandwidth limitations of the earlier "g-seats" resulted in effective sinusoidal transport delays (Appendix B) ranging from 75 ms (Ashworth, 1976) to values well in excess of 100 ms

(McGuire and Lee, 1979; Showalter, 1978), the corresponding delay introduced by the new seat was only 20 ms. This provided sufficient headroom for integrating the new seat into a research simulator while controlling the total simulator delay to satisfy the 100 ms criterion suggested by Howe et al., (1978). (Total simulator sinusoidal transport delays were actually held to 75 ms—see Chapter 2.)

The research laboratory included a whole-body motion device, capable of one-to-one motion about the roll axis. Thus a criterion device, against which the effectiveness of tactual cuing could be compared, was also available.

In order to enhance the likelihood of finding a motion effect for tactual cuing, an experimental task was chosen which had already been shown to be sensitive to the presence (or absence) of whole-body motion information (Levison et al., 1979). This task simply required subjects to maintain themselves upright in the presence of a non-predictable disturbance which perturbed them about the roll axis. Error was visually presented on a small, centrally located visual display, as described in Chapter 2. Motion information was the factor of primary concern in the study; the appropriate level of motion was presented either in the dynamic seat or the criterion motion device. (The experimental protocol is discussed in Chapter 3.)

Some researchers feel it is not sufficient that pilots achieve similar performance levels, but (because pilots can so readily adapt to compensate for simulator deficiencies) it is also necessary that they adopt the same control behavior in the simulator as in the aircraft (Hall, 1978; Puig et al., 1978). It was therefore elected to compare control behavior as well as performance among different treatment groups. Performance was measured in terms of tracking error (i.e., angular deviation from "wings-level flight"), which could be recorded directly. Control behavior could be assessed in control terms in the steady state frequency domain; this required that the human operators' steady state describing function be identified. An analysis program was available which would accomplish this, under the assumption that the human operator could be approximated as a noisy, time invariant, linear process as illustrated in Fig. 1. Further constraints required that the controlled plant be linear and time invariant, and that the disturbance forcing function have stationary statistical properties. The experimental task was designed so that the

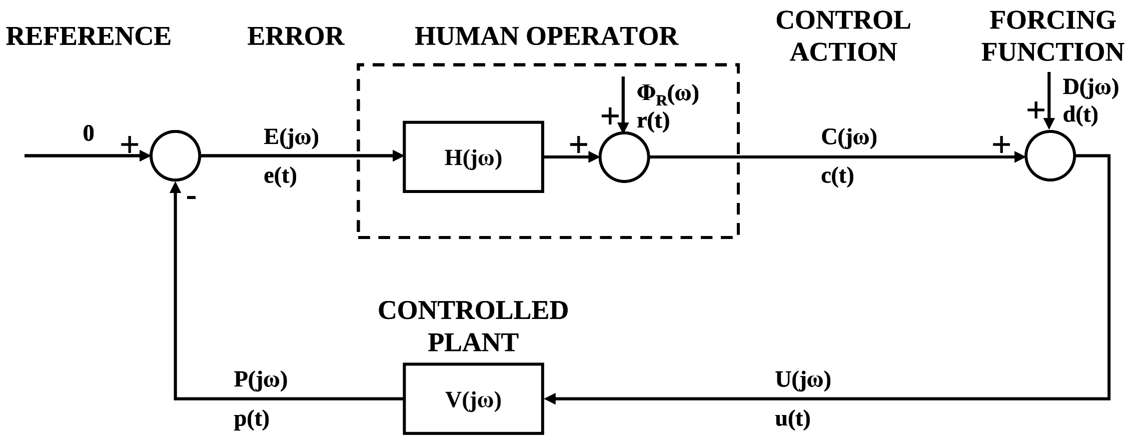

Figure 1. Block diagram of a single axis, compensatory display, disturbance regulation tracking task

In this case, the human operator is considered a quasi-linear element in a feedback control loop (see McRuer et al., 1965). The human operator's response is assumed to be characterizeable as a noisy, time invariant, linear process. That is, the human operator's control output is assumed to consist of a signal linearly correlated with the external forcing function plus a stochastic signal ("remnant") linearly independent of the forcing function. The measurement and identification techniques used in this experiment further require that the controlled plant dynamics be (reasonably) linear and time invariant, and that the forcing function have stationary statistical properties (Levison, 1982).

d(t) or D(jω) = Disturbance Forcing Function
p(t) or P(jω) = Controlled Plant (Vehicle) Position
e(t) or E(jω) = System Error
c(t) or C(jω) = Operator's Control Action
r(t) or $\Phi_R(\omega)$ = Operator Remnant Referred to Output
u(t) or U(jω) = Summed Plant Rate Command
H(jω) = Operator Describing Function
V(jω) = Controlled Plant (Vehicle) Dynamics

identification techniques developed by Levison (1982), and embodied in the analysis program, could be applied. The analysis program was used to identify the human operator and the open loop describing functions, among others. Four "crossover variables"—selected to be sensitive to changes in control behavior resulting from different motion conditions (Appendix E)—were extracted from the open loop describing function (Section 3.5). These served as dependent variables in the comparisons of control behavior reported in Chapter 4.

1.2 Research Objectives

The role of the vestibular organs in motion perception and dynamic spatial orientation has been extensively explored and modeled (e.g., Meiry, 1965), but the tactile and kinesthetic (tactual) sensors' role is not so well defined (Borah et al., 1977; Borah et al., 1979; Clark and Horch, 1986; Zacharias, 1978). The data presented in this report are intended to contribute to the body of knowledge regarding situations where tactual sensory afferents are interpreted as motion information.

There were two specific experimental goals. The first was to determine whether a human operator could learn to use motion information provided by a seat pan display to develop a level of performance and control behavior equivalent to that adopted in the whole-body motion environment. The second goal, since there was no guarantee that equivalent behavior would lead to good transfer, was to determine how the developed skill and control behavior transferred to the full motion environment.

1.3 Research Approach

A research laboratory appropriate for the pursuit of the research objectives was available and, fortuitously, had been configured to support an experimental task which had been demonstrated to be sensitive to the quality of displayed motion information (Levison et al., 1979). This laboratory included a candidate criterion device capable of one-to-one, whole-body motion about the roll axis. The dynamic seat was integrated into this laboratory, and the simulator fine-tuned to support the research described in this report. A detailed description of the simulator configuration is presented in Chapter 2.

The experimental task (discussed at length in Chapter 3) was the compensatory (i.e., only error was displayed), roll axis, disturbance regulation task diagrammed in Fig. 1. Task dynamics were limited to the roll axis so that human performance in the dynamic seat could be compared to that in the available roll-axis, whole-body motion equipment. Key task variables were maintained as closely as possible to those employed by Levison et al., (1979).

Before the experiment could begin, a viable drive law had to be developed for the dynamic seat. No systematic, objective approach had previously been undertaken to develop dynamic seat drive laws for rotational motion onset cuing. Thus a substantial amount of preliminary work (described in Appendix A) was necessary in order to determine how to effectively present the tactual information. The most surprising result of this work was that, contrary to conventional wisdom, drive laws based upon buttocks pressure matching or upon presentation of acceleration cues were not very effective. Two drive laws which did show promise were based upon displaying position and velocity information. These are expressed in Equ.(A-11) and Equ.(A-12) respectively.

In order to satisfy the two research objectives, the experiment was broken down into a training phase followed by a criterion phase. Training was carried out under four motion conditions, with each subject assigned to one of the conditions. These included a static condition (visual cues only), two dynamic seat conditions (a position and a velocity drive law), and a full motion condition (see Tables 3 and 4). During the criterion phase all subjects tracked with whole-body motion. In order to demonstrate equivalence, or lack thereof, planned comparisons of the tracking performance and control behavior scores (the latter in terms of four crossover model parameters) of the four groups were carried out using univariate tests described later. (Analysis results are presented in Chapter 4.)

Significant differences between the static and full motion groups' scores late in the training phase would demonstrate that performance and control behavior were indeed modified by the presence (or absence) of useful motion information. Lack of significant differences between dynamic seat and full motion group scores would be an indication that the group members were performing/behaving equivalently.

Planned statistical tests of all group scores were made for the following events (see Chapter 4).

1. Late training (the last four training sessions; each session consisted of four 3-minute tracking runs)

2. Transition (the last training run and first criterion run)

3. Post-transition (the first, fourth, seventh, and last criterion session)

In addition, Human Operator Describing Functions obtained from late training and late post-transition data are presented as a qualitative demonstration of the effects-of-motion information provided under training conditions and in the criterion device. The operators' generation of lead equalization in the presence-of-motion information can be observed directly in these plots (Fig. 13 through 20).

It seemed reasonable to expect that the different levels of motion might affect the rate of skill acquisition, under the assumption that useful motion information would facilitate operator identification of the correct order of the controlled plant dynamics (Levison, 1983). For this reason an asymptotic model was fit to each individual's training scores, subject to certain goodness-of-fit constraints (Appendix C). A point estimate for each subject's rate of tracking skill acquisition was thereby obtained (Section 4.2.2) for statistical analysis.

1.4 Organization of the Report

The introductory material in Chapter 1 is expanded upon, including relevant supporting rationale, in the remaining chapters. The "Background" section in Chapters 2, 3, and 4 is intended to serve as the link between this introductory overview and the content of those chapters. Relevant material is sometimes repeated in order to cause each chapter to stand reasonably on its own. Chapter 2 details the implementation of Fig. 1, including descriptions of the motion and tactual display equipment, the forcing function, and the configuration and timing of the various simulator loops. Chapter 3 discusses the experimental methodology, data reduction techniques, and the statistical procedures. Chapter 4 presents the data, details the methods of analysis, summarizes the results of each block of tests, and reports the conclusions to be drawn from those analyses. Chapter 4 also includes the results of several unplanned Analyses of Variance (ANOVAs) comparing post-transition performance and control behavior scores for subjects trained under the static and two dynamic seat conditions to the scores for the untrained motion subjects; this was done to determine the effects training had on the scores. Chapter 5 provides an overview of the major findings of the experiment and suggests further research in this area. The preliminary work which laid the foundation for this experiment and some of the earlier data and findings are presented in Appendix A. The remaining Appendices provide supplementary material referenced elsewhere from the body of this report.

CHAPTER 2

Description of the Simulation

2.1 Background

The four key task variables having a major effect on operator dynamics are the forcing function, display, manipulator, and controlled plant (McRuer and Jex, 1967). The nature of this experiment required that these task variables be defined so as to assure that the subjects would use available motion information. The simulation was therefore designed around the key task variables of a previous experiment conducted at the Wright-Patterson Air Force Base AFAMRL facility wherein the task was shown to be motion sensitive (Levison et al., 1979). A minor change in the controlled plant dynamics was necessitated by the addition of the dynamic seat; this resulted in a total effective pure time delay of 75 ms, rather than the 60 ms transport lag appearing in the earlier experiment's plant. One other change from the conditions of the earlier experiment was the location of the axis of rotation of the Roll Axis Tracking Simulator (RATS), which was used as the criterion whole-body motion device in the current experiment. In the earlier study, the RATS rolled about an axis which was located at approximately head height. AFAMRL researchers felt that it would be more appropriate to move the roll axis to seat-pan height in order that it more resemble the situation in an aircraft; this was done prior to using the RATS in the current experiment.

The experiment was conducted using a hybrid simulator complex at the AFAMRL facility. Existing equipment was used without modification to the extent possible. The "dynamic seat" or "g-seat" portion of the Advanced Low Cost G-cuing System (ALCOGS), which was installed in the AFAMRL facility for this experiment, was used to train the subjects. The RATS (already in place in the facility) and the ALCOGS were integrated into a common hybrid simulator. Mathematical models of the simulated vehicle and motion display hardware dynamics were implemented on an EAI 580 Analog Computer integrated with a Digital Equipment Corporation (DEC) PDP11/60 digital computer. Continuous system dynamics were modeled on the analog computer, while the digital computer was used to control timing, to inject pure time delays, to generate the "disturbance" forcing function, and to collect data. The basic simulator update rate was 100 Hz (for reasons discussed in Section 2.8); data were collected at 25 samples per second in order that existing data collection software could be used. Simulator hardware and software are described in more detail in the following sections.

2.2 The Equipment—An Overview

A conceptual block diagram of the simulator configuration is shown in Fig. 2. The human controller is considered as an element in a control loop, responding to displayed information and regulating a roll-axis, gust-like disturbance in order to minimize the roll error. The human operator's control input was through an isometric, right side-arm control stick, with its static gain calibrated at 16 degrees/s commanded roll velocity per pound applied force (Section 2.4). The simulated vehicle was representative of a fighter-like aircraft with a roll subsidence (i.e., rate command input to vehicle velocity response) time constant of 200 ms. Transport delays, introduced because of the sampled-data nature of the simulation, are shown as a part of the vehicle dynamics. De-aliasing filters, a 10 ms "order delay", and data reconstruction filters (zero-order holds) together contributed an effective transport lag of 45 ms (Section 2.9). The dynamic seat and its associated DAC low-pass filters, because of their relatively high bandwidth, could together be approximated as a transport delay of 30 ms (Section 2.7). This resulted in a total effective transport lag of 75 ms around the motion display loop. The dynamics of the RATS were not so wide-band, and so were modeled on the analog computer as a low pass filter with a single pole at 20 rad/s (Section 2.6).

The simulation was designed such that the controlled plant dynamics (including the simulated vehicle, RATS, and dynamic seat along with any associated low pass filters and digital delays) were the same regardless of the signal path taken around the motion display loop (Fig. 6 and 7). The dynamics around the visual display path (Fig. 4) were matched to those of the motion signal path to within 4 ms.

In summary, the controlled plant dynamics were:

$$\frac{P(s)}{U(s)} = \frac{16}{s} \cdot \frac{1}{0.2s+1} \cdot \frac{e^{-0.075s}}{0.05s+1} \qquad \text{(2-1)}$$

where P(s) is the simulated RATS cab roll angle in degrees and U(s) is the applied control force in pounds. The numerator dynamics include the stick gain and the total effective transport delay. The denominator dynamics include a pure integrator (which converts roll velocity to roll angle) plus the simulated vehicle (time constant of 0.2 seconds) and simulated RATS (time constant of 0.05 seconds) lag dynamics.

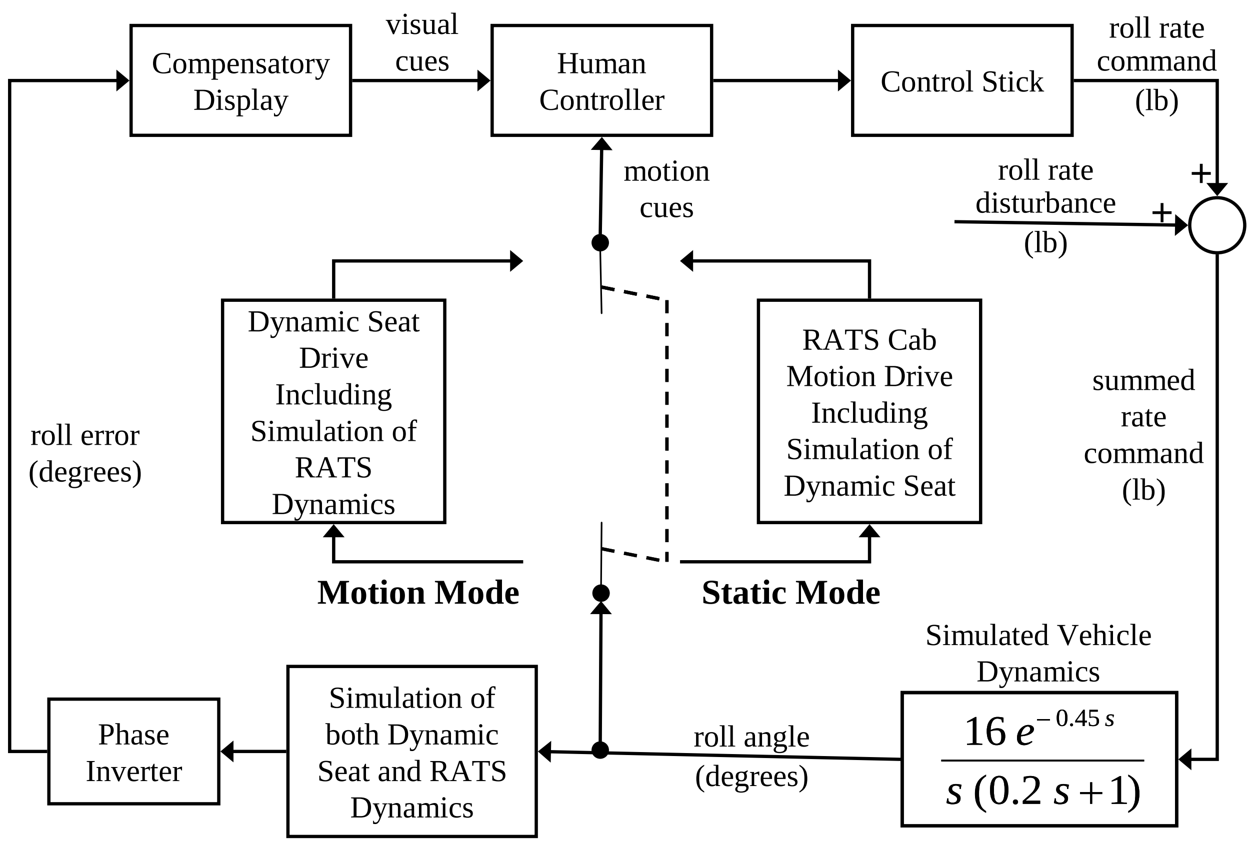

Figure 2. Conceptual block diagram of the experimental configuration

The roll axis was the only simulated degree-of-freedom. Subjects were instructed to maintain the simulated vehicle level in the presence of a random-appearing, gust-like roll disturbance. Subjects regulated this disturbance using a right-handed isometric control stick; the control stick gain (16 degrees/s/lb) was included in the vehicle dynamics. The 45 ms delay in the vehicle dynamics resulted from low pass de-aliasing filters (30 ms), a 10 ms order delay, and a 5 ms Zero Order Hold delay. The Roll Axis Tracking Simulator (RATS) was simulated as a low pass filter with a single pole at 20 rad/s, and the dynamic seat was simulated as a pure time delay of 30 ms (these models are not shown in this figure). The total transport delay around the motion display loop was therefore 75 ms. Visual information was relayed to the operator via a compensatory display on a television monitor. Non-visual motion information was displayed either through the dynamic seat or the full-motion RATS; the mode switch position shown corresponds to static cuing.

2.3 The Visual Display

Visual roll error was displayed on a standard 9 inch diagonal television screen. The viewing distance was nominally 26 inches, with the television mounted within 10 degrees of eye level. Subjects were instructed to adjust the brightness and contrast controls for comfortable viewing.

Visual information was provided via a compensatory display wherein the displayed error was equal to the roll angle. Error was represented by the roll of an aircraft symbol (which was the level reference) relative to a dashed line fixed with respect to the screen (Fig. 3).

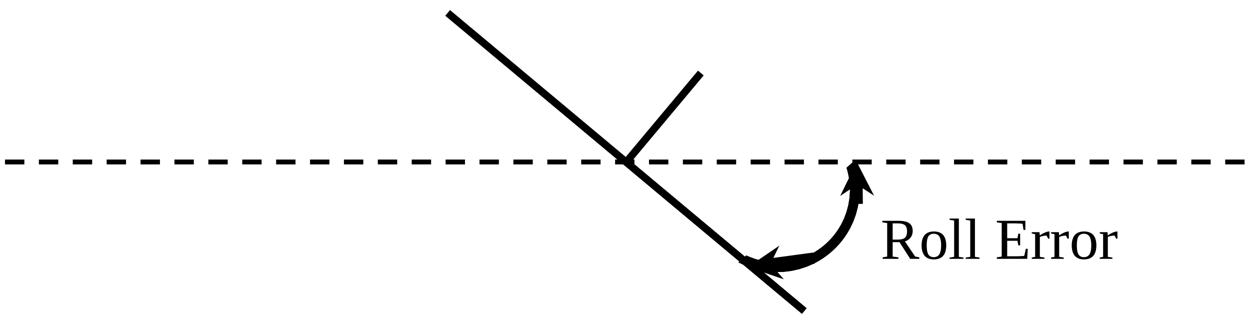

Figure 3. The compensatory display provided for the roll axis tracking task
This was displayed on a standard 9-inch diagonal television screen mounted within 10 degrees of eye level for each subject; contrast and brightness were adjusted by each subject for comfortable viewing. The dashed line was fixed relative to the screen and represented "ownship" attitude. The aircraft symbol was the level reference or "horizon." Subjects were instructed to attempt to maintain the aircraft symbol "wings" aligned with the dashed line. The length of the dashed line was 4 inches, the aircraft symbol wingspan was 1.5 inches, and the vertical fin was 0.375 inches long. Viewing distance was nominally 26 inches (resulting in the dashed line subtending about a 9-degree angle), varying somewhat according to the tracking posture adopted by the operator. One degree of displayed error corresponded to one degree roll error.

A block diagram of the visual display implementation, from the simulated vehicle rate command input through to the display on the television screen, is shown in Fig. 4. The roll error was generated by sampling the analog model position (including both simulated vehicle and RATS dynamics) every 10 ms, injecting a digital delay to match the time delay in the visual signal path to that of the motion display signal path, inverting to convert roll position to roll error, and then displaying the roll error on a DEC VR14 graphics monitor. The VR14 display was then converted to a standard television video signal by photographing the graphics display with a COHU Series 2810 monochrome television camera, using existing equipment. The video signal was finally routed to the television monitors through coaxial cable.

The display of the error on the VR14 involved a sample-and-hold operation with a 10 ms sampling interval; the linear phase characteristic of this zero-order hold operation corresponds to a time delay of 5 ms (Rosko, 1972). Conversion of the VR14 graphics display to a standard television display was, in essence, a second sample-and-hold operation with a corresponding time delay of 16.7 ms. Pure time delays around the visual display path totaled 71.7 ms. This matched the delays around the motion display signal path to within 4 ms.

2.4 The Control Stick

Identical side-arm force-actuated control sticks (Measurement Systems Inc., Model Number 435 M/S-151) were mounted on the operator's right-hand side in both the ALCOGS enclosure and the RATS cab. The control stick mounting configuration is visible in Plates I and III. Armrest pads were fixed with velcro strips to the top of a firm armrest which provided forearm support. Subjects were encouraged to position the pad to a comfortable position.

Controller gain was originally derived for use in the earlier experiment (Levison et al., 1979) on the basis of the gain schedule being used in the F-16 aircraft. In order that the control stick not unduly contribute to the remnant, it was necessary to eliminate stick deadband and other non-linearities from the F-16 gain schedule. This was accomplished by using a linear approximation to the aircraft data which yielded a stick gain of 16 deg/s per pound force applied 3.75 inches above the force transducer diaphragm. (The convention of expressing controller gain in terms of applied force rather than torque is a carry-over from the way in which the aircraft data were presented.)

2.5 The Disturbance "Sum-of-sines" Forcing Function

The disturbance used was identical to that previously used by Levison et al., (1979) in the earlier experiment which demonstrated a task sensitivity to motion cuing. The disturbance was composed of 13 sinusoids with their amplitudes weighted to represent white noise passed through a low-pass filter with a double pole at 2.0 rad/s. This disturbance was developed for the earlier study using the optimal control pilot model technique described by Junker and Levison (1977). It met five criteria proposed by Levison (1982).

1. Each component frequency was harmonically related to the reciprocal of the run length, but to none of the other component frequencies. Constructing the disturbance in this way permits the estimation of remnant by simply averaging power measurements over frequency bands on either side of the input frequency components, and permits describing functions to be estimated as the ratio of Fourier coefficients—rather than requiring the averaging of cross spectral quantities (Levison, 1982).

2. The number of sinusoids was sufficient that the disturbance appeared to be random. Levison (1975) suggested that as few as five sinusoidal components would suffice for this purpose.

3. The effective bandwidth of the input was selected to be reasonably wide, without making the task so difficult as to unrealistically affect tracking behavior.

4. The amplitudes of the component sinusoids were selected to approximate a specific spectral density function (i.e., white noise passed through a low-pass filter). Doing this makes the forcing function compatible with existing pilot models, such as the optimal control pilot/vehicle model (Levison and Junker, 1977).

5. The phase relationships among the component sinusoids were randomly changed from run to run to prevent subjects from learning the input.

The 13 sinusoidal amplitudes were adjusted for an overall rms value of 0.875 lb (14 deg/s rms when multiplied by the control stick gain). Individual component amplitudes are shown in Table 1.

Each component sinusoid was generated digitally and the composite disturbance was output to the analog computer, where it was summed with the “control stick” command. In order that all recorded signals were properly synchronized (or “time-tagged”), it was necessary to record the

Table 1. Disturbance sum-of-sines components

The composite signal had an rms value of 0.875 lb (14 deg/s rms when multiplied by the control stick static gain). Zero db corresponds to one lb-rms. The exact run length, determined by dividing the number of samples collected (4096 samples) by the sampling frequency (25 samples/s), was 163.84 s. The reciprocal of the run length, which is the frequency resolution obtainable from a Digital Fourier Transform of the sampled time series (Gold and Rader, 1969), was therefore 0.0061 Hz or 0.0383 rad/s.

CYCLES PER	FREQUENCY		AMPLITUDE	
RUN LENGTH	rad/s	Hz	lb-rms	db
5	0.192	0.031	0.385	–8.3
13	0.499	0.079	0.424	–7.5
28	1.074	0.171	0.399	–8.0
37	1.419	0.226	0.310	–10.2
53	2.033	0.323	0.286	–10.9
73	2.800	0.446	0.229	–12.8
105	4.027	0.641	0.168	–15.5
149	5.714	0.909	0.109	–19.3
209	8.015	1.276	0.068	–23.4
288	11.045	1.758	0.043	–27.3
417	15.992	2.545	0.026	–31.7
573	21.974	3.497	0.016	–36.2
835	32.022	5.096	0.010	–41.1

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disturbance signal actually perturbing the plant dynamics. Therefore, the disturbance signal recorded was actually the sampled analog signal, as is shown in Fig. 5.

2.6 The Criterion Device: The Roll Axis Tracking Simulator (RATS)

The RATS was used as the whole-body motion criterion device in this study. The RATS cab consisted of a 28 inch wide, 68 inch high, 76 inch long, rigid, rectangular, cage-like structure built of welded 1.5 by 3.0 inch steel box beams (visible in Plate I). The cab was covered by a translucent vinyl-coated cloth covering which served to shroud external visual references from the operator (Plate II shows the RATS with the covering in place). An aircraft seat, with the seat pan modified to resemble the ALCOGS seat pan (including the “tuberosity blocks” and “thigh ramps” discussed in Section 2.7), was mounted within the cab. A television monitor was mounted in the cab within 10 degrees of eye level and at a nominal viewing distance of 26 inches. A footrest (which was easily removable, and used in both the RATS and ALCOGS) was mounted on the cab floor and adjusted in the fore-aft direction to a comfortable position for each subject; velcro strips attached to the footrest were used to secure each subject's feet in place.

The RATS cab was pivoted fore and aft so that it could completely roll about an axis passing through the center of the cab at seat pan height. Slip rings were used to interface the cab to the remainder of the simulator. The cab was powered by a General Electric 10 horsepower direct current motor (visible in Plates I and II at the extreme right end of the drive train) controlled by computer commands through a GE SP200 Speed Variator Special Purpose Drive. Motor output was coupled to the cab through a low-backlash gear reduction drive (Ex-Cell-O Cone Drive Operations Model SHV7700C-1, 30:1 gear ratio). Total measured drive train backlash was 0.4 degrees. With this configuration, the measured maximum RATS cab motion capabilities were:

Roll Excursion:	360 deg (continuous)
Roll Velocity:	180 deg/s
Roll Acceleration:	1150 deg/s/s

The unlimited roll capability was not used in this experiment. During tracking trials, RATS cab excursions were software limited to a 90 degree roll angle. As in the earlier referenced study, an operator was assumed to have lost control if the 90 degree limit was encountered. (This software limit was imposed as it was necessary to define an upper roll limit for purposes of scaling the analog computer simulation. Once this limit was encountered, amplifiers saturated on the EAI 580, and the simulation was no longer valid.)

A BAFCO Model 916 Frequency Response Analyzer was used to characterize the velocity response of the RATS cab in the frequency domain. It was found that it could be roughly approximated as a linear first-order filter with a pole at 20 rad/s—similar to its response prior to the modifications made to shift the axis of rotation (Levison et al., 1979). However, at frequencies above 35 rad/s the response was quite amplitude dependent. This nonlinear behavior was attributed to drive train backlash, which was not practical to reduce further. In order to

Plate I. RATS cab and drive train with the cab interior exposed

Plate II. RATS cab and drive train with the translucent fabric covering in place Velcro strips, used to close the ingress/egress flap (shown in the open position), formed a light-tight seal during data collection

force the RATS to behave as a linear system, a low-pass filter of the form $(0.05\ s + 1)^{-1}$ was implemented on the analog computer, and a model following technique (Levison and Zacharias, 1977) used to force the cab to follow the modeled dynamics. A block diagram of the RATS drive is presented in Fig. 6. The results of a typical "daily readiness" autopilot run comparing model response to actual cab response is provided in Table 2. (Autopilot implementation is shown in Fig. 5.) It is seen that the cab tracked the modeled filter response quite well up to about 11 rad/s.

Table 2. Frequency domain comparison of the modeled cab position response to that of the actual cab position

Fourier coefficients were estimated from a sampled time history of the MODEL POSITION record and CAB POSITION record of a typical autopilot run, and the relative GAIN and PHASE obtained from the complex ratio of the Fourier coefficients. Recorded CAB POSITION lagged the recorded MODEL POSITION because of the way these signals were recorded. In Fig. 6 it can be seen that the CAB POSITION signal underwent an additional 10 ms digital delay, 5 ms zero-order hold delay, and nominal 30 ms (more precisely 28.5 ms; see Appendix B) delay due to a low-pass de-aliasing filter. The CORRECTED PHASE accounts for this 43.5 ms offset in recording the signals. A GAIN of 0 db and CORRECTED PHASE of 0 deg indicate that the model and cab signals are matched in amplitude and in time, respectively.

FREQUENCY rad/s	FREQUENCY Hz	GAIN db	UNCORRECTED PHASE degrees	CORRECTED PHASE degrees
0.192	0.031	0.0	0.5	0.0
0.499	0.079	0.0	1.2	0.0
1.074	0.171	0.0	2.5	–0.2
1.419	0.226	0.0	3.3	–0.2
2.033	0.323	0.0	4.7	–0.4
2.800	0.446	–0.1	6.4	–0.6
4.027	0.641	–0.2	8.9	–1.1
5.714	0.909	–0.5	12.1	–2.1
8.015	1.276	–1.5	15.9	–4.1
11.045	1.758	–3.6	29.5	2.0
15.992	2.545	–6.5	77.0	37.1

$$\text{DESCRIBING FUNCTION} = \frac{\text{RECORDED MODEL POSITION}}{\text{RECORDED CAB POSITION}}$$

2.7 The Dynamic Seat

The dynamic seat was used to provide broad area, tactual motion information to subjects during training. The dynamic seat used in this experiment was the “g-seat” subsystem of the ALCOGS built by the Link Division of the Singer Company for AFHRL. It is described in detail by Kleinwaks (1980); a more general description is presented in Kron and Kleinwaks (1978). The seat cuing device, in its delivered configuration, included hydraulically actuated backrest and seat pan plates overlaid by pneumatically actuated “firmness bladders.” The lap belt could be independently driven, as could two radial wing elements located at the lower outboard corners of the backrest; the lap belt and radial wing elements were hydraulically actuated. All actuators and dynamic elements were packaged in an aircraft seat appearing similar to the type used in modern tactical aircraft (Plate III). The backrest was reclined 20 degrees from the vertical in the ALCOGS, as was the backrest in the RATS seat.

Plate III. Dynamic seat, shoulder harness, and lap belt in operational configuration

"Tuberosity blocks," intended to emphasize buttocks pressures in the vicinity of the ischial tuberosities, were mounted to the upper surface of the seat pan plate. These were two aluminum blocks, 0.125 inches thick and approximately 2.13 inches square, which were centered 6.25 inches behind the forward edge of the seat and 1.92 inches to the left and right of seat pan centerline.

"Thigh ramps", intended to emphasize pressures along the outer buttock and upper thigh areas, were also mounted to the upper surface of the seat pan plate. These were aluminum blocks which were 3 inches wide, 14 inches long, and beveled at a 30 degree angle. These blocks provided the seat pan contouring.

Both the tuberosity blocks and the thigh ramps are visible in Plate IV.

Plate IV. Dynamic seat pan plate with the tuberosity blocks and thigh ramps exposed
Also visible are two square "seat-occupied" pressure switches (not to be confused with the tuberosity blocks) which are forward of, and further outboard than, the tuberosity blocks.

The “firmness bladders” were not used in this experiment. The primary reason for this resided in their frequency response (Kleinwaks, 1980). Despite the fact that the gain was above the –3 db point out to 8 Hz, the phase delay introduced by the pneumatic servo controlling the bladders was considered excessive for use in this study. Applying the general construct outlined in Appendix B, but using a least squares fit to the data rather than an analytic approximation, the equivalent pure time delay introduced by the bladders was found to be 92 ms. This much delay introduced by a single display element would have easily driven the total simulation delay beyond the 100 ms maximum recommended by the USAF Scientific Advisory Board’s Ad Hoc Committee on Simulation Technology (Howe et al., 1978).

The firmness bladders were replaced by a 0.375 inch thick closed cell foam pad on the seat pan, and by a one inch thick open cell foam pad on the backrest. The reason for the thicker foam on the backrest was to mimic the soft backrest of the RATS seat. The thinner pad was used on the seat pan in order to preserve any useful seat cues arising from the tuberosity blocks and thigh ramps. There was no problem in matching the RATS seat pan “feel” to that of the ALCOGS seat since the RATS seat pan had been modified to include tuberosity blocks and thigh ramp contours similar to those in the ALCOGS. The same foam padding was used on both seat pans.

The removal of the pneumatic servo actuators from the simulator simplified the problem of matching the response of all dynamic seat actuators, since all hydraulic actuators had similar characteristics (Kleinwaks, 1980). A BAFCO Model 916 Frequency Response Analyzer was used to tune all hydraulic servo loops to a –10.5 deg phase angle at 1.5 Hz. The actuators then exhibited the characteristics of a second order system with an undamped natural frequency at 11.6 Hz and a damping ratio of 0.707. At low frequencies, this response was equivalent to a pure time delay of 19.3 ms (Appendix B).

The seat’s dynamic backrest plate was not used during the course of this study. Early in the investigations regarding how the seat was to be used to provide motion information, it was decided that the backrest degrees of freedom were not appropriate for generating the proper cues. This was based upon subjective evaluations regarding the kind of flesh scrubbing and pressures experienced in the full motion environment of the RATS versus cues which the ALCOGS backrest was capable of providing. Further, backrest motion appeared to produce more head motion—and hence unwanted, and not necessarily appropriate, vestibular stimulation—than did a similar amount of seat pan motion. This was due to the fact that the backrest operated directly on the shoulders, with the resulting motion coupled directly to the neck and head.

For reasons discussed in Appendix A (Section A.7), lap belt and “radial element” cues were not provided. This left the seat pan plate (with its tuberosity blocks and thigh ramps) as the only active seat cuing device used in this experiment.

The seat pan was driven in accordance with the algorithms derived during the preliminary work described in Appendix A. The drive laws are repeated here from Equ.(A-11) and Equ.(A-12) for the reader’s convenience.

The Position Drive Law was:

$$\textit{Seat Roll}\ \text{(degrees)} = \left(\frac{1}{3}\right) \bullet \textit{Model Roll}\ \text{(degrees)} \quad \text{(2-2)}$$

The Velocity Drive Law was:

$$\textit{Seat Roll}\ \text{(degrees)} = \left(\frac{1}{8}\right) \bullet \textit{Model Velocity}\ \text{(degrees/s)} \quad \text{(2-3)}$$

The digital computer solved the appropriate drive law and generated the command to the dynamic seat actuators in real-time, as shown in Fig. 7. DAC outputs to the dynamic seat actuators were processed by second order, low-pass, adjustable bandwidth filters resident in the ALCOGS electronics cabinet. The phase delay introduced by these filters was minimized by maximizing their bandwidth, while reserving enough adjustment tolerance to permit matching their response. Filters were matched by setting them for a 90 degree phase lag at 50 Hz (which set the undamped natural frequency at 50 Hz). Measurements with the BAFCO Frequency Response Analyzer indicated a damping ratio of 1.5 at this adjustment. From Appendix B, the low frequency response of these DAC output filters was equivalent to a pure time delay of 9.6 ms. When cascaded with the seat’s servoactuator lag of 19.3 ms, the delay involved in displaying motion information with the dynamic seat totaled 28.9 ms. This was reasonably close to a multiple of the simulator sampling interval. The combined seat actuator and DAC filter dynamics were therefore simulated as a pure time delay of 30 ms, which was readily implemented on the digital computer (see Section 5.4 in Gold and Rader, 1969).

2.8 Data Recording and Simulator Sampling Rates

Experimental data were recorded digitally. Data collection software, developed for an earlier study (Levison et al., 1979), was available and used without modification. The analog disturbance, controller, model position, and RATS cab or dynamic seat position signals were sampled and recorded 25 times a second. It was decided to make the overall simulator update rate an integral multiple of the 25 Hz data sampling rate in order to avoid undue complications to the control logic. With this constraint and consideration of operating system and real-time computational requirements, it was determined that the maximum rate which could be supported was 100 Hz (hence, a 10 ms sampling interval).

Data recording was automatically initiated after 15 seconds had elapsed at the beginning of each run (this allowed subjects time to stabilize themselves before "scoring" commenced). Once initiated, data were recorded every fourth computational frame for a period of 165 seconds. As a result, 4125 samples were recorded for each of the four data channels. (The first 29 samples were later discarded prior to data analysis. This left 4096 samples collected over an observation period of 163.84 seconds—exactly one period of the fundamental frequency of the disturbance signal (Table 1).)

2.9 Digital Computer Input/Output Processing

All ADCs and DACs were serviced at the beginning of each computational frame. Input/output processing was initiated by a real-time clock interrupt occurring every 10 ms. This assured a regular sampling interval for both inputs and outputs, but also resulted in a 10 ms "order delay" (i.e., digital computer throughput required a minimum of 10 ms). In addition to this obligatory "order delay," delays were sometimes deliberately inserted in order to match delays around each of the various signal paths as shown in Fig. 4 through Fig. 7.

Low-pass filters preceded all samplers (ADCs) in the simulator. This was done to attenuate any high frequency power present in the signal in order to avoid any significant frequency "foldover" or "aliasing" effects (Gold and Rader, 1969). The de-aliasing filters present in the system had a second-order Butterworth characteristic with a natural frequency of 49.6 rad/s. The gain of these filters was –8.4 db at 12.5 Hz (the data sampling foldover or Nyquist frequency). Since this seemed adequate, no modification was made to the existing filters. In Appendix B it is shown that these de-aliasing filters introduced a phase delay equivalent to a pure time delay of 28.5 ms (a nominal value of 30 ms is used).

Computer outputs were passed through desamplers, or data reconstructors, which served to create a continuous signal from the sampled signal. The desampler consisted of a DAC followed by a "sample-and-hold", or "zero-order-hold" (ZOH), circuit. The linear phase characteristic of a ZOH corresponds to a time delay of one-half the sampling interval (Rosko, 1972). The normalized gain of a ZOH with a 10 ms sampling interval is essentially unity over the frequency range of interest (the gain rolls off to –0.004 db at 11 rad/s, the highest frequency of interest (Appendix B)). Therefore, the ZOH is well approximated as a pure time delay of 5 ms.

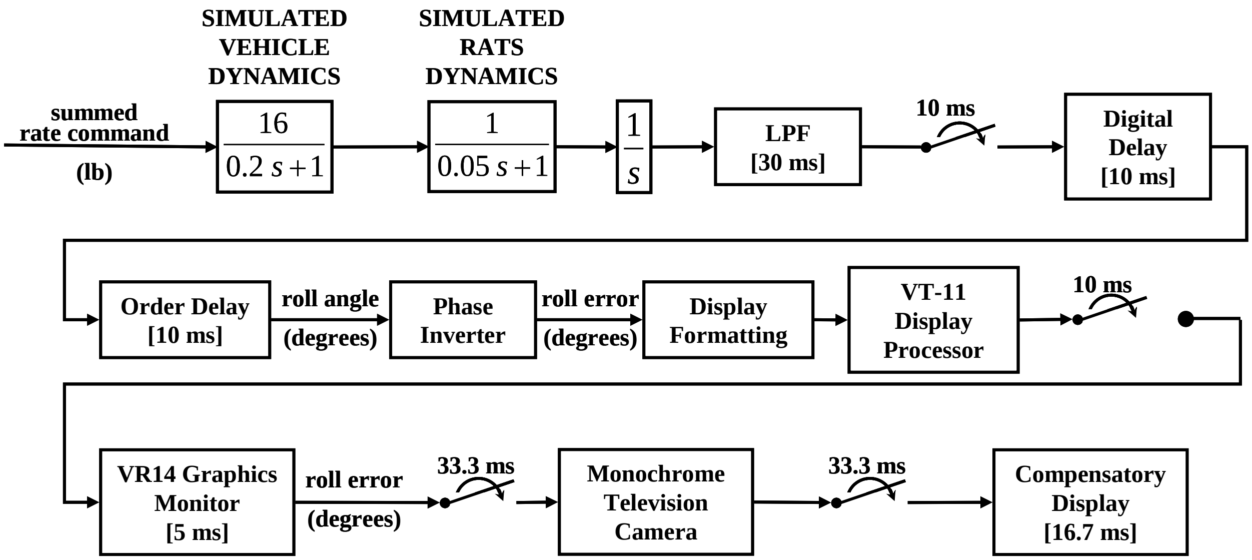

Figure 4. Block diagram detailing implementation of the Visual Display Loop

The vehicle and RATS cab dynamics were modeled on an EAI 580 Analog Computer. Low pass filters (LPF), used to reduce aliasing, introduced a phase lag equivalent to a 30 ms delay. Model position was sampled every 10 ms. A digital delay was inserted in order to match the visual display temporal delays to those of the motion displays. An “order delay” of 10 ms resulted from the 10 ms sampling period. Roll error, which was just model position with a phase inversion, was then formatted and input to a DEC VT11 Display Processor; the output of the display processor was sampled every 10 ms, and the result held on a calligraphic display. This sample-and-hold operation introduced a 5 ms delay. The output of the VR14 calligraphic display was then sampled every 33.3 ms by a television camera and displayed on a standard television screen. This latter sample-and-hold operation resulted in an additional delay of 16.7 ms. Samplers are indicated using the conventional schematic representation (Truxal, 1955); sampling intervals are noted above, or next to, the sampler. Pure time delays are shown within brackets in the appropriate blocks. The total transport delay for the visual signal path was 71.7 ms, which led to a mismatch of less than 4 ms with respect to the motion display signal path.

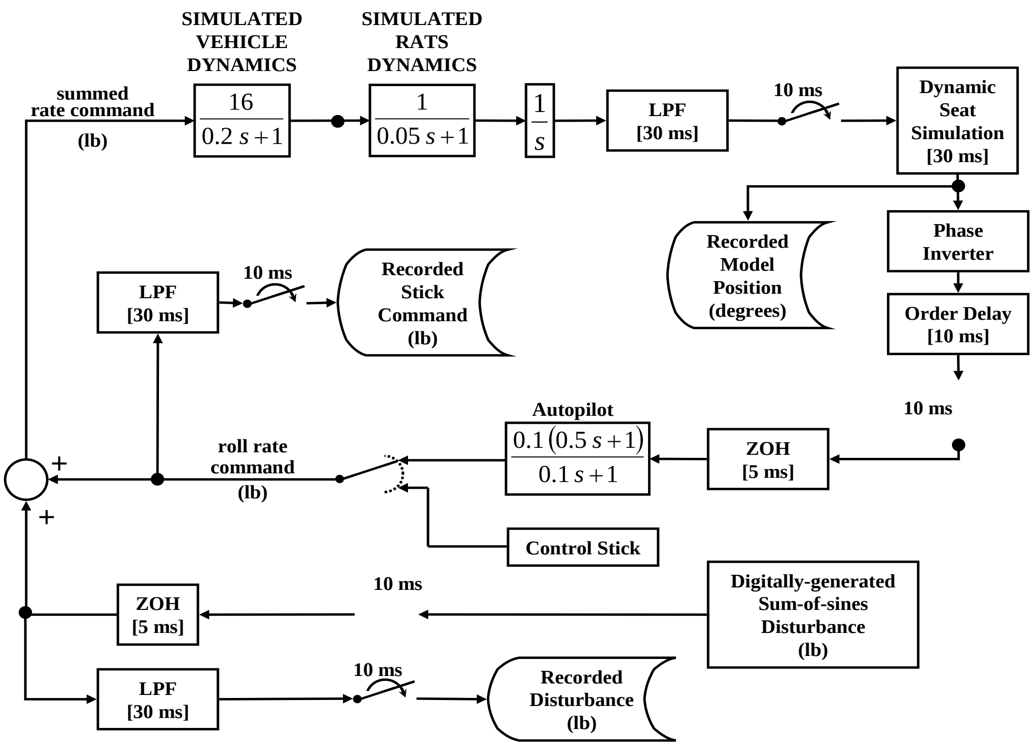

Figure 5. Block diagram detailing implementation of the Autopilot Loop

The technique used to assure that the recorded disturbance data was properly synchronized with recorded position data is shown. The vehicle and RATS cab dynamics were modeled on an EAI 580 Analog Computer. Low pass filters (LPF), used to reduce aliasing, introduced a phase lag equivalent to a 30 ms delay. Model position was sampled every 10 ms, and the sampled position was delayed to account for the dynamics of the dynamic seat before being recorded. The phase inversion converted roll position to roll error. The "order delay" of 10 ms resulted from the 10 ms sampling period. Roll error was output to the autopilot (which was implemented on the analog computer) via a zero-order-hold (ZOH); this introduced a 5 ms delay. The autopilot dynamics used mimicked the linear response of a relatively poor tracker in a static environment, and resulted in the feedback coupling being sufficiently loose that autopilot runs were reasonably sensitive to any anomalies in system performance. Autopilot runs therefore provided a ready means for conducting daily system readiness checks. The roll rate command used to close the loop was selectable between the autopilot and control stick outputs (here shown in the "autopilot" mode). The control stick or autopilot output was then summed with the roll rate disturbance, resulting in the net "summed rate command" to the simulated vehicle dynamics. Although the disturbance was generated digitally, it was the analog signal which was recorded—after it had been low pass filtered (LPF) and sampled. In this way the recorded disturbance was assured to be properly time-tagged to the recorded control stick and model position signals. Samplers are indicated using the conventional schematic representation (Truxal, 1955); sampling intervals are noted above, or next to, the sampler. Pure time delays are shown within brackets in the appropriate blocks.

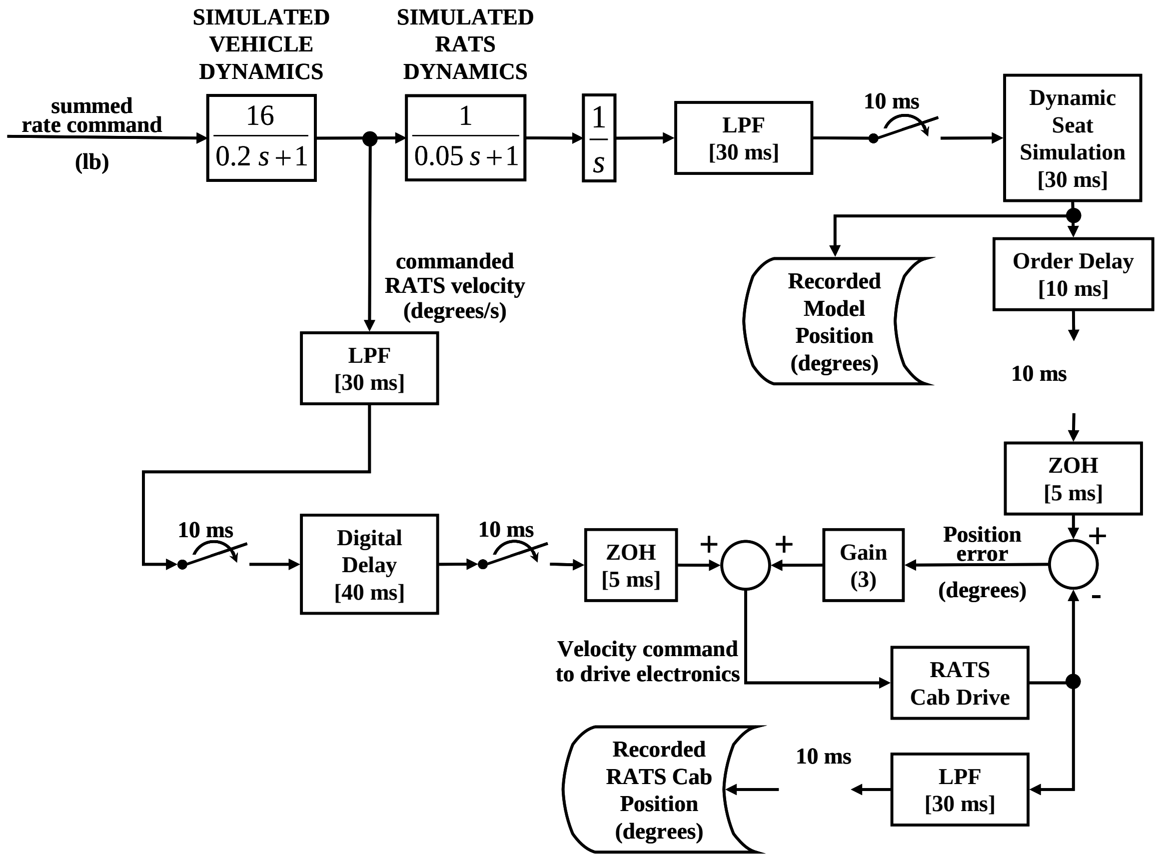

Figure 6. Block diagram detailing implementation of the Roll Axis Tracking Simulator (RATS) cab drive

The vehicle and RATS cab dynamics were modeled on an EAI 580 Analog Computer. A model following technique (Levison and Zacharias, 1977) was used to force the RATS cab to follow the modeled dynamics; both model and actual cab positions were digitally recorded so that the accuracy with which the slaved cab follows the model could be monitored. The low pass filters (LPF), used to reduce aliasing, introduced a phase lag equivalent to a 30 ms delay. The dynamic seat and its associated DAC filter dynamics were together simulated as a 30 ms delay. Note that the “recorded model position” accounted for the simulated dynamics of both the RATS and the dynamic seat. An “order delay” of 10 ms resulted from the 10 ms sampling period. The commanded RATS cab velocity (output from the vehicle dynamics model) was sampled and subjected to the same total digital delay as was the sampled model position. The sampled RATS velocity command and model position were then reconstructed via zero-order-holds (ZOH); this sample-and-hold operation introduced an additional 5 ms delay. The reconstructed velocity command was then summed with a weighted cab position error (the weight gain was set to a nominal value of 3 degrees/s/degree); the output of the summer was the resultant velocity command input to the RATS Drive Electronics.

Samplers are indicated using conventional schematic representation (Truxal, 1955); sampling intervals are noted above, or next to, the sampler. Pure time delays are shown within brackets in the appropriate blocks. The total transport delay for the RATS cab drive signal path was 75 ms.

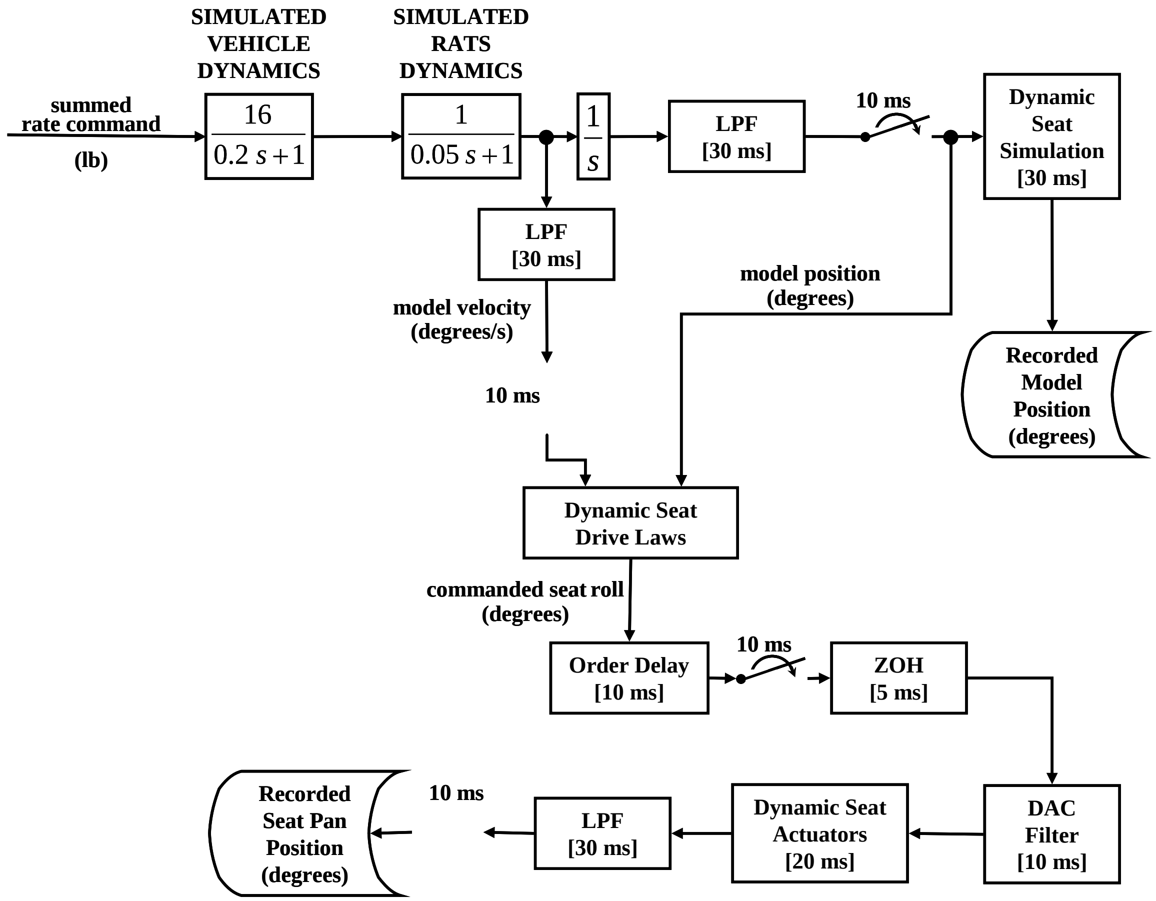

Figure 7. Block diagram detailing implementation of the Dynamic Seat Drive

The vehicle and RATS cab dynamics were modeled on an EAI 580 Analog Computer. Low pass filters (LPF), used to reduce aliasing, introduced a phase lag equivalent to a 30 ms delay. Model position and model velocity were sampled every 10 ms, and used to update the drive law command to the dynamic seat. Note that the "recorded model position" accounted for the simulated dynamics of both the RATS and the dynamic seat. An "order delay" of 10 ms resulted from the 10 ms sampling period. The resulting seat roll commands were reconstructed via zero-order-holds (ZOH); this sample-and-hold operation introduced an additional 5 ms delay. The output of the ZOH was filtered in order to smooth the steps due to signal quantization; this DAC filter, with a bandwidth of 50 Hz and a damping ratio of 1.5, introduced a phase delay equivalent to a 10 ms transport delay. The dynamic seat actuators, which had a bandwidth of 11.8 Hz and 0.707 damping, were characterized as a pure time delay of 20 ms. Samplers are indicated using conventional schematic representation (Truxal, 1955); sampling intervals are noted above, or next to, the samplers. Pure time delays are shown within brackets in the appropriate blocks. The total transport delay for the dynamic seat signal path was 75 ms.

CHAPTER 3

Experimental Design and Data Reduction

3.1 Background

The purpose of this experiment was to investigate whether a human operator could learn to use broad area, dynamic tactual information provided through a seat pan to develop a level of performance and control behavior equivalent to that which would be adopted in a full motion environment, and then carry this skill level over into a whole-body motion environment. To accomplish this, tracking data were collected from subjects receiving motion information displayed through a seat pan, from subjects in a whole-body motion environment, and from subjects provided visual cues only. Performance is analyzed in terms of tracking error, and control behavior is analyzed in terms of variables extracted from describing function estimates. This chapter describes the experimental protocol and the techniques used in data reduction. The analyses and results are presented in Chapter 4.

3.2 Description of the Experiment

The apparatus used in the experiment has been described in detail in Chapter 2. A block diagram of the tracking task is illustrated in Fig. 2.

The experimental task required subjects to maintain "wings-level" flight in the presence of a random appearing roll disturbance. The disturbance was composed of thirteen sinusoids with their amplitudes weighted to resemble low-pass filtered white noise (Section 2.5). Disturbance power was concentrated at frequencies selected to facilitate identification of the human operator quasi-linear describing function (Levison, 1975; Levison, 1982). Phase relationships among the component sinusoids were randomly varied from run to run so that subjects would not learn the waveform. A nonpredictable forcing function was necessary in order to minimize "predictor operator" effects so that a non-zero reaction time would be assured and the influence of the motion information would be enhanced (e.g., Frost, 1972; Gregory, 1976; Jaeger et al., 1979; McRuer and Krendel, 1957; Stark, 1968; Zacharias and Levison, 1978). Simulated vehicle roll dynamics represented those of a fighter class aircraft (Section 2.2). Roll error was presented via a compensatory display on a centrally located, small television monitor (Section 2.3). An isometric, right side-arm control stick was used by subjects to make tracking inputs (Section 2.4). Tracking was accomplished in either the dynamic seat simulator (Section 2.7) or the Roll Axis Tracking Simulator (RATS; Section 2.6), in accordance with the assigned training condition. Subjects wore a helmet and were secured by a lap belt, shoulder harness, and foot restraints for all tracking sessions. An intercom set integrated into the helmet enabled communication between the subject and experimenter. White noise, piped into the helmet headphones, served to mask background sounds (each subject adjusted the white noise volume for a comfortable level). A light-tight enclosure around the dynamic seat and a translucent shroud around the RATS cab deprived subjects of external visual references in either simulator.

A simulator autopilot (Fig. 5) run was conducted at the start of each day as a check for proper equipment operation.

The experiment was designed with four treatment groups in order to obtain the data necessary to accomplish the research objectives. Six subjects, balanced to account for possible differences due to sex, were assigned to each group. It was expected that a group size of six would be sufficient on the basis of differences observed between static and full motion subjects in data taken from an earlier experiment employing the same task variables (Levison et al., 1979). Naive (i.e., no previous piloting or similar tracking experience), young, predominantly right-handed subjects of generally good health were used in order to maximize homogeneity within the subject population.

Subjects were assigned to one of four training conditions (Table 3) on the basis of a pretest described later. Each subject was then given 80 training runs under the assigned condition. Training was scheduled so that subjects would receive two sessions of training per day, with a break of 30 to 45 minutes between sessions. Each session consisted of four 3-minute tracking runs, with a break of 60 to 90 seconds between runs. Subjects were given 15 seconds to stabilize themselves at the beginning of each run before data collection commenced. RMS tracking error was displayed to each subject upon completion of a run.

After completing 80 training runs (20 sessions), subjects were transitioned to the criterion whole-body motion environment of the RATS. Tracking and data collection continued in the RATS for an additional 40 post-transition runs (10 sessions).

To maintain motivation, tracking error scores were posted for the current subject set. Best and worst trackers' scores for each of the training conditions, taken from earlier studies, were included on the charts to provide each subject reference performance data for his or her condition.

Table 3. Training conditions

Subjects were given 80 training trials under one of the four tabulated conditions before being transitioned to the criterion whole-body motion environment. STATIC subjects were assigned to either a static dynamic seat or a static RATS cab condition as a control for equivalence between the two simulator environments; these assignments were balanced to compensate for order effects. The dynamic seat Position Drive Law and Velocity Drive Law are given by Equ.(2-2) and Equ.(2-3) respectively.

GROUP IDENTIFIER	TRAINING DEVICE	MOTION CONDITION
STATIC	DYNAMIC SEAT/RATS	Seat/Cab Static
POSITION	DYNAMIC SEAT	Seat Pan Active Position Drive Law
VELOCITY	DYNAMIC SEAT	Seat Pan Active Velocity Drive Law
MOTION	RATS	Whole-body, One-to-one Motion

3.3 Subject Orientation, Pretest, and Assignment to Training Conditions

Subjects were run in sets of four, with one subject assigned to each of the training groups. A total of six such subject sets participated sequentially in the experiment.

Each subject set was provided a formal orientation briefing in order to assure that all subjects were similarly apprised of the research objectives, the experimental task, the training conditions, and scoring procedures. Following this briefing, subjects were asked to read and sign a consent form (reproduced in Appendix D).

Subjects were next given a short familiarization tracking session with a simple disturbance forcing function consisting of a fundamental frequency at 1.1 rad/s (0.2 Hz) and its third harmonic; this composite practice disturbance signal had an rms value of 2 lb. The purpose of this familiarization session was to acquaint subjects with the controlled plant dynamics and the error display—control stick relationship, while not providing them practice with the experimental disturbance signal. The subjects were secured into the RATS cab and sequenced through the following events with the cab static.

(1) No disturbance input was presented, but subjects had stick control for 60 seconds. This permitted subjects to gain some experience with the controlled plant dynamics.

(2) The practice disturbance was applied, but under autopilot control, for 30 seconds. This permitted subjects to passively observe the disturbance profile.

(3) The practice disturbance was applied, and subjects were required to track for 60 seconds. Tracking error was scored during this time.

Subjects were then recycled through the same sequence with the cab in motion. The scoring phase of this familiarization session with cab motion doubled as the pretest, the tracking scores of which served as a basis for training group assignment.

A list of "tracking hints" (Appendix D, Section D.3), which were evolved during the earlier pilot work described in Appendix A, was handed to each subject upon completion of the familiarization session. It was thought that these notes would mean more once subjects had initially experienced the tracking environment and could better relate to them.

Data collection began the day following the orientation and familiarization session. Pretest scores were used to match the groups with the constraint of balancing sex within each group. Subject assignments and relevant data are provided in Table 4.

Table 4. Subject training condition assignments

Naive, young, typically right-handed (or at least able to track with both hands with equal ease) subjects of generally good health were used. Training condition assignments were made so as to match average pretest scores across groups. STATIC subjects were assigned to either a static dynamic seat simulator condition (S), or to a static RATS cab condition (R).

SUBJECT NUMBER	SUBJECT AGE	SUBJECT SEX	PREFERRED HAND	PRETEST SCORE	TRAINING CONDITION
001	22	M	RIGHT	6.20	VELOCITY
002	22	M	LEFT	9.18	POSITION
003	22	M	RIGHT	9.19	STATIC(S)
004	22	M	RIGHT	4.81	MOTION
005	21	F	RIGHT	10.79	POSITION
006	22	F	RIGHT	14.66	MOTION
007	22	F	RIGHT	12.53	VELOCITY
008	20	F	LEFT	5.77	STATIC(R)
009	20	M	RIGHT	5.96	MOTION
010	20	M	RIGHT	11.13	STATIC(R)
011	23	M	RIGHT	5.15	POSITION
012	19	M	RIGHT	6.78	VELOCITY
013	19	F	RIGHT	8.77	VELOCITY
014	19	F	RIGHT	11.87	POSITION
015	20	F	RIGHT	8.20	STATIC(S)
016	24	F	RIGHT	8.92	MOTION
017	22	M	RIGHT	6.93	MOTION
018	21	M	RIGHT	6.33	POSITION
019	23	M	RIGHT	38.44	STATIC(S)
020	23	M	RIGHT	9.16	VELOCITY
021	22	F	RIGHT	9.46	VELOCITY
022	24	F	RIGHT	8.52	POSITION
023	20	F	RIGHT	5.21	STATIC(R)
024	21	F	RIGHT	15.58	MOTION

PRETEST SCORE GROUP AVERAGES

STATIC	POSITION	VELOCITY	MOTION
12.99	8.64	8.82	9.48

3.4 Transformation of Time History Data into the Steady-state Frequency Domain—Estimation of Describing Functions and Remnant Power

Four tracking loop variables were digitally recorded as described in Section 2.8. The analog disturbance (Fig. 5), control stick output (Fig. 5), model position (Fig. 5, 6, and 7), and RATS cab/dynamic seat pan position (Fig. 6 and 7) were sampled and recorded 25 times per second for 165 seconds. Of the 4125 samples recorded, the last 4096 (the requisite power of two for efficient fast Fourier transforms; Gold and Rader, 1969) were retained for subsequent analysis. This resulted in a 163.84 second observation period, and consequent frequency resolution of 0.038 rad/s in the transform domain. In addition to the four recorded variables, the summed rate command (Fig. 5) was obtained by adding the sampled values for the control stick and disturbance. The resulting five time records were then subjected to analysis using an available program similar to the "Performance Analyzer's" performance analysis package described by Zacharias and Levison (1978, Appendix A). This analysis program was used to perform the Fourier transform operation, to estimate the input-correlated and remnant power at each of the input frequencies, and to compute the describing functions. The relevant variables were written to magnetic tape for subsequent analysis.

Steady state, frequency domain describing functions were estimated as described below for the human operator (H), the plant (V), and the open loop (HV) dynamics. The following relationships apply (refer to Fig. 1).

$$H(j\omega) = \frac{Controller\ Output,\ C(j\omega)}{Displayed\ \ Error,\ E(j\omega)} \qquad \frac{\text{(pound - force)}}{\text{(degree)}} \quad \text{......................(3-1)}$$

$$V(j\omega) = \frac{Model\ \ Position,\ P(j\omega)}{Summed\ \ Rate\ Command,\ U(j\omega)} \qquad \frac{\text{(degree)}}{\text{(pound - force)}} \quad \text{......................(3-2)}$$

$$HV(j\omega) = \frac{Controller\ Output,\ C(j\omega)}{Summed\ \ Rate\ Command,\ U(j\omega)} \qquad \frac{\text{(pound - force)}}{\text{(pound - force)}} \quad \text{......................(3-3)}$$

In addition, the ratio of the model position to the RATS cab/dynamic seat pan position was computed (a typical result for an autopilot run is shown in Table 2) as a check for equipment malfunctions or degradation.

Following the example of Levison (1982), estimates of remnant power were obtained by averaging over a ¼ octave window centered at each input frequency (excluding the frequency interval where the input power was concentrated). Remnant power could be estimated in this way (under the assumption of constant $H(j\omega)$ across the window) since input power was concentrated at specific frequencies selected to minimize leakage (Section 2.5). Where power at the input frequency (corrected for remnant) was sufficiently greater than the remnant power at the adjacent frequencies (the 6 db criterion suggested by Zacharias and Levison (1979) was used), the Fourier coefficient was considered sufficiently uncorrupted by remnant (i.e., "reliable") to use in the estimation of describing functions. Describing function estimates at each input frequency were simply computed as the complex ratio of the Fourier coefficients when both the numerator and denominator could be considered "reliable." (The 6 db criterion was tantamount to requiring that at least 80% of the measured power be correlated with the input signal before the linear describing function estimate was considered reliable. Stated another way, this required a linear correlation coefficient of at least 0.9—i.e., the square root of 0.8—for "reliable" estimates.)

Remnant signals are characterized by continuous and smooth spectra (e.g., Levison et al., 1969; Levison, 1982; McRuer and Jex, 1967). The power spectral density of the control stick closed-loop remnant at each input frequency was therefore estimated as the average remnant power per rad/s in the ¼ octave window. The use of a sum-of-sines forcing function enhanced the accuracy of the estimates for remnant power since these are free of the errors introduced by the apparent cross correlation between input and remnant which occurs with forcing functions that are continuous in frequency (Levison, 1982).

3.5 Estimation of Crossover Variables

Human dynamic behavior for closed loop tracking tasks of the type used in this experiment are suitably characterized in control theory terms in the steady state frequency domain (Jex, 1971). Motion information is known to cause modifications in control behavior in that subjects operate with more high frequency lead equalization, and consequently can increase their low-frequency gain without sacrificing closed loop stability (e.g., Shirley, 1968). Modifications in lead equalization and gain resulting from various levels of motion information can be directly observed in the human operator describing function H(jω). In order to parsimoniously quantify this effect for different motion conditions, it was decided to estimate crossover model parameters which would capture its essence (Appendix E). The analysis program was modified to obtain run-by-run estimates of crossover frequency (ω_C), the phase angle at crossover (φ_C), the low-frequency open loop gain (K_L), and the gain "rolloff" in the vicinity of ω_C. These four parameters serve to directly capture the consequences of control behavior modifications resulting from different motion conditions.

HV(jω) was already available from the analysis program results. The only assumption necessary to extract K_L and "rolloff" from |HV(jω)| was that a linear fit would be appropriate over a range of frequencies extending from about 1.0 rad/s to just beyond ω_C. A least squares fit algorithm (e.g., Neter and Wasserman, 1974) was implemented in the analysis program to fit all "reliable" |HV(jω)| estimates over the appropriate frequency range. The following model was fit.

$$Y(\omega) = g_0 + g_1(\log \omega) \quad \text{(3-4)}$$

where Y(ω) is the expected value of |HV(jω)| at frequency ω, g_0 is the estimate for K_L, and g_1 is the estimate for "rolloff". In order to avoid the fit from being distorted by the high frequency neuromuscular/sampling resonance above ωC (Jex, 1971; McRuer, 1966; Stark, 1968), it was necessary to exclude |HV(jω)| estimates at frequencies above 6.0 rad/s from the fit. Otherwise estimates for all frequencies from 1.0 rad/s to (and including) the input frequency just above ω_C were used. Following the initial training runs, the standard error of the estimate typically took on values on the order of 0.5 db (with the exception of the VELOCITY group for which errors on the order of 1 to 2 db were not unusual throughout dynamic seat training). During early training the errors tended to be higher, with values sometimes as high as 2 to 3 db.

Estimates for ω_C and φ_C were computed by linear interpolation. An algorithm was added to the analysis program which performed an interpolation between the two input frequencies where

$|HV(j\omega)|$ crossed from positive to negative values in order to estimate the frequency corresponding to a 0 db amplitude ratio. This frequency was accepted as the estimate for ω_C. The phase angle corresponding to ω_C was similarly computed by interpolating between the two $\underline{/HV(j\omega)}$ phase angle estimates. This phase angle was accepted as the estimate for φ_C. The phase margin (φ_M) was obtained by adding 180 degrees to φ_C.

The appropriateness of the estimates for the crossover parameters so obtained was evaluated by co-plotting these on numerous single-run Bode plots of $HV(j\omega)$. The tracking data used for this evaluation were obtained from an earlier study using the same task variables as this experiment (Levison et al., 1979), and included whole-body motion and static subjects in both early and late stages of training. In all cases, the estimates for the crossover parameters appeared to reasonably represent the data.

3.6 Statistical Tests

The intent of this research was to compare performance and control behavior among subject groups with four different motion conditions. Performance was measured along a single dimension—rms tracking error. Control behavior was measured along four dimensions—ω_C, φ_M, K_L, and gain rolloff (see Appendix E). The multi-dimensional nature of the dependent variables, and the known correlations among tracking error, ω_C, and K_L (McRuer and Jex, 1967) suggested a problem appropriate for multivariate analysis (Reising et al., 1977). After initial consideration, it was elected not to pursue the use of multivariate techniques however. This decision was partially based upon analyses performed on data collected by Levison et al., (1979). The results of these analyses suggested that if the differences between group scores were going to be large enough to have any operational significance, these differences would show up in univariate tests on either tracking error or crossover frequency. It was also felt that the results of univariate tests would be more readily interpretable than a multivariate composite function. Consequently, it was decided to apply univariate tests to the data. Boneau (1960) points out that—if precautions are taken—classical normal theory techniques are virtually immune to violations of the underlying assumptions of normality and homogeneity of variance. On this basis, it was opted to rely on the robustness of established classical procedures rather than less powerful, and less readily available, nonparametric analyses. In order to minimize the consequences of any departures from normality and homogeneity of variance, group sizes were maintained equal with an equal number of scores obtained for each subject (Boneau, 1960; Kirk, 1968).

Differences in performance/control behavior between all groups were of interest. Therefore multiple comparison tests were employed using the procedures recommended by Kirk (1968) to control the Type I error rate at the generally accepted level of p=0.05 for each dependent variable's family of comparisons; Kirk's terminology is employed where applicable. It was assumed in general that the subjects comprising the experimental groups were a random sample from a population of subjects, permitting conclusions to be generalized to the population. All treatment effects were assumed fixed. Hence, the "mixed model" applied to all tests. The *general procedures adopted from Kirk* are *outlined below*, with further detail provided in the discussion of each test in the remainder of this report.

(1) An appropriate analysis of variance (ANOVA) was first applied to test for significant main effects and significant interactions. The Type I error was controlled at p=0.05 for this overall F-test. Tests involving repeated measures on each subject (specifically Randomized Block and Split Plot Factorial designs) are positively biased if the underlying assumptions of homogeneity of variance or homogeneity of covariance are violated (Kirk, 1968); Kirk therefore recommends that the Geisser-Greenhouse conservative F-test be used for these tests. In order to avoid the ambiguity which arises with this test when the conventional F-test is significant but the conservative F-test is not, the convention adopted in this report was to simply use the conservative F-test results.[1] ANOVA tables presented report significance for both the CONVentional and CONServative F-tests where repeated measures were involved; however only the

[1] It has been the experience of researchers at AFAMRL that differences large enough to have operational significance will normally be detected by the conservative F-test. The computational labor added by exact multivariate analyses to resolve the ambiguity was not warranted.

conservative F-test result was used as a basis for rejecting the null hypothesis of equal means.

(2) If a significant interaction was detected in the first ANOVA, then a second "significant interaction" ANOVA was employed to test for simple main effects. In this case the overall level of p was divided evenly among the collection of simple main effect tests (the actual level of p used is provided in the discussion of the relevant tests). Since an interaction suggests that one factor behaves differently under different levels of the other factor, significant main effects were of little interest for independent variables involved in a significant interaction. Instead, interest was confined to the simple main effects for these variables.

(3) For those independent variables for which a significant main effect or simple main effect was detected, posteriori comparisons were conducted to determine which pairwise comparisons between the means were significant. This was done using the Tukey HSD (honestly significant difference) Multiple Comparison Test. The error rate for the family of comparisons was controlled at 0.05 for main effects or the appropriate level of significance (the same as that used in the "significant interaction" ANOVA) for simple main effects. The "critical difference" is the magnitude of the difference detectable at the corresponding level of significance. This is provided in the Tukey's Test tables.

Pairwise comparisons between means are not necessary when only two factor levels are involved, as this comparison is redundant to the ANOVA. Nonetheless, the Tukey Test tables are provided for these instances as a convenient and consistent means of reporting both the critical difference and the difference between the means.

There are tests for which the possibility of some general interest in the magnitude of the differences exists regardless of their statistical significance. These include the tests for performance differences at transition (i.e., the last training run versus the first full motion run) and the comparisons of performance between no-motion and dynamic seat trained subjects versus untrained full motion subjects. For these tests the Tukey Test Table is included for those factors likely to be of interest, but the results are annotated as "Reference only" if the preceding ANOVA did not detect a significant effect.

(4) A significant F ratio indicates that some association exists between the dependent variable and the factor levels, but provides no information regarding the strength of that association. A trivial effect can achieve statistical significance with sufficiently large sample sizes (Hays, 1963; Kirk, 1968). Conversely, a very low strength of association is an indication that very little can be predicted regarding the treatment effects on the dependent variable, and that further pursuit of the issue with a larger sample size or other refinements of the experiment may offer little potential for payoff (Hays, 1963). For these reasons both Hays and Kirk strongly recommend that results be interpreted in terms of strength of association (i.e., the estimated proportion of the variance in the dependent variable accounted for by the independent variable) as well as statistical significance. Strength of association (SOA) is therefore reported on the overall F-test ANOVA tables. These values were computed using the procedures recommended by Hays (1963) and Kirk (1982).

CHAPTER 4

Results and Discussion

4.1 Background

The objectives of this experiment, as stated in Chapter 1, were to (1) determine whether a human operator could learn to use broad-area tactual motion information provided through a seat pan to develop a level of performance and control behavior equivalent to that which would be adopted in a whole-body motion environment, and (2) to determine how this developed skill and control behavior would transfer to the full motion environment. Dynamic seat drive laws were designed for minimal head motion in order that the haptic system would be the primary non-visual modality for the pick-up of motion information (Appendix A).

To accomplish the stated objectives, training data, transition data, and late post-transition data are compared for the four subject groups (trained under STATIC, POSITION, VELOCITY, and MOTION conditions—as discussed in Chapter 3). Tracking performance is compared in terms of rms tracking error, whereas frequency domain describing function variables are employed to compare control behavior. Rms tracking error is considered an appropriate measure of performance since subjects were instructed to minimize tracking error, and were shown their rms tracking error scores at the end of each run.[2] Relevant describing function variables for comparing control behavior are open loop man-vehicle crossover frequency (ω_C), gain (K_L), phase margin (φ_M), and the rate of change of open loop gain with log frequency in the vicinity of crossover (rolloff); these variables serve to define the man-vehicle frequency domain describing function in a region where the effect of motion information is pronounced (Appendix E). The influence of motion information on control behavior for tasks similar to that employed here is reported widely in the literature (e.g., Jex et al., 1981; Levison et al., 1979; Ringland and Stapleford, 1971; Shirley, 1968; Stapleford et al., 1969). Specifically, the literature reports that subjects in this type of task environment use available motion information to generate more high

[2] McRuer and Jex (1967) argue that minimizing tracking error is, at least for well-trained operators, equivalent to minimizing the mean-square error.

frequency lead compensation than is possible with visual information alone. This, in turn, permits the subject to increase gain—and hence crossover frequency—without sacrificing stability (phase margin). Had all treatment groups adopted similar phase margin and rolloff characteristics, crossover frequency alone would have sufficed to capture the overall effect of the presence, or absence, of useful motion information. This was not the case however—as will be seen. Therefore all four frequency domain variables are necessary to develop a complete picture regarding differences in control behavior among the four groups.

The experimental data, averaged across the six subjects in each group, are plotted versus tracking runs in Fig. 21 through 40.[3] In each of these figures, the group average, plus and minus one standard deviation, is shown for each run. The plotted data for runs 1 through 80 show the group scores under their respective training conditions. The data for runs 81 through 120 show group scores after transition to the RATS whole-body motion environment. (The MOTION group, of course, didn't actually undergo a transition since their training took place in the whole-body motion environment.)

STATIC group training was split between the static dynamic seat and the static RATS cab as a control for equivalence between these two simulator environments (Table 3). Prior to conducting other statistical tests, the STATIC group scores were tested using an appropriate ANOVA.[4] Once it was confirmed that no statistically significant effects due to the different static environments existed, the STATIC group scores were pooled for use in subsequent analyses.

The experimental results are presented as follows. Tracking error performance is treated first in Section 4.2. Average performance late in training is compared for all four groups in Section 4.2.1. Following this, Section 4.2.2 presents the results of fitting the tracking scores

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[3] All Figures and Tables referenced from within this chapter that contain data or experimental results are located together at the end of this chapter to facilitate cross referencing and comparisons.

[4] A Split Plot Factorial design with factors "training device" and "sessions" was used where repeated measures were involved (Kirk, 1968). Otherwise a Single Factor ANOVA with two levels of "training device" was used (Neter and Wasserman, 1974).

obtained during training to an asymptotic model. This effectively collapses the 80 tracking scores for each subject down to three model parameters. As will be seen, these model parameters correspond to estimates for asymptotic performance, learning rate, and the change in performance during training. Section 4.2.3 then summarizes the results of the comparisons of training performance data. Tracking performance in transition from the training to the criterion whole-body motion environment is treated in Section 4.2.4, and Section 4.2.5 looks at tracking across the post-transition period. Section 4.2.6 summarizes the findings of the analyses of the transition to criterion and post-transition data.

Section 4.3 treats the frequency domain variables in essentially the same order as the tracking error results are presented in Section 4.2. No asymptotic model parameter estimates are provided, however. It had been expected that the asymptotic model would be appropriate to characterize the variation of the frequency domain variables with training (this was based upon the examination of a limited sample of data from an earlier study using the same task variables). As it turned out, asymptotic fits for the frequency domain variables were often appropriate for only three to four subjects per group (this varied with treatment condition), in accordance with the a priori goodness-of-fit criteria presented in Appendix C. Asymptotic model fits for those cases where the least squares solution did not satisfy the goodness-of-fit criteria could be found by backing off from the least squares solution to an acceptable value for the learning rate. However, the parameter estimates so obtained would no longer be the maximum likelihood estimators (Stevens, 1951). It was expected that parameters derived in such fashion would have a strong potential for being biased. Further, with so many instances of lack-of-fit, it was not clear from the data at hand that the asymptotic model was generally appropriate for the frequency domain variables. It is possible that if training had been extended over a longer period such that asymptotes were better defined, the model fits with least squares estimates for the parameters would have been successful.

4.2 Tracking Error Performance

Fig. 21 through Fig. 24 show how tracking error varied over the course of the experiment.

Tracking error during training was compared by testing for differences in average "late training" performance.[5] Asymptotic model parameters, obtained from an Asymptotic Regression Program (Dixon, 1973), were tested for differences in asymptotic performance, learning rates, and the amount of tracking error change among the four groups.

Tracking error performance at transition was tested for group differences over runs 80 and 81, the last training and first post-transition run respectively.

Post-transition performance was analyzed by comparing tracking errors over sessions 21, 24, 27, and 30. This provides insight regarding transfer of the trained skill for early, mid, and late post-transition performance spread over equal intervals.

Since differences in performance between all four groups were of interest, multiple comparison tests were employed in accordance with the procedures recommended by Kirk (1968). That is, a Tukey Multiple Comparison Test was applied when an ANOVA indicated that a significant difference existed among the means. Type I errors were controlled at the generally accepted 0.05 level of significance.

4.2.1 Tracking Error Late in Training

Attention is directed to the tracking scores obtained over runs 65 through 80 (Fig. 21 through Fig. 24). These scores were compared in a planned ANOVA using a Completely Randomized Factorial (CRF) layout, which is an appropriate design for the two between block factors involved (Kirk, 1968). There are four levels of "Drive Law" and two levels of "Sex". The results, presented in Table 6, indicate a significant main effect of "Drive Law" (Factor A), but no detectable differences due to "Sex" (Factor B). The strength of association shows that Factor A

[5] It was planned, a priori, to define "late training" as including runs 65 through 80 so that the sample space would include more than one day's data from each subject.

accounts for 92% of the variance in the ANOVA. This suggests a strong relationship between "Drive Law" and tracking error. Having determined that the main effect of Factor A is significant, the next step was to proceed to determine <u>which</u> pairwise comparisons were significant. The Tukey Multiple Comparison Test results (bottom of Table 6) show that the STATIC group was performing at a level of performance significantly poorer (i.e., higher tracking error) than all other groups, and that the POSITION group was performing more poorly than the MOTION group. However, the performance of the VELOCITY group was not detectably different from that of the MOTION group at a p=0.05 level of significance. This serves to demonstrate that motion information was improving task performance, and that it is possible to provide wide-area tactual motion information through the seat which elicits tracking performance equivalent to that achieved in a whole-body motion environment. (The Tukey Test critical difference, with the error rate for the family of pairwise comparisons controlled at p=.05, is 0.81 degree tracking error.)

<u>4.2.2 The Asymptotic Model Fit to Tracking Error During Training</u>

It was possible to fit each subject's tracking error scores during training (runs 1 through 80) to an asymptotic model which satisfied the goodness-of-fit criteria in Appendix C. Levison et al., (1979) had suggested the use of such a model to facilitate comparison of learning rates among subject groups.

The asymptotic model is an exponential decay model of the form:

$$Y(n) = Y_A + B \bullet [1 - R]^{(n-1)},\ 0<R<1 \text{ and } n = 1, 2, 3, \ldots \qquad \text{..............................(4-1)}$$

where Y(n) is the score for run n,Y_A is the estimated asymptotic performance score, and B is the amount of change Y(1)–Y_A. R is the learning rate defined as the fraction by which the difference between current performance and asymptotic performance is reduced from run to run. That is,

$$R = \frac{Y(n) - Y(n-1)}{Y_A - Y(n-1)} \qquad \text{..(4-2)}$$

The least-square estimates for the three model parameters, Y_A, B, and R, were obtained using an available BMD Asymptotic Regression Program (Dixon, 1973). The steepest descent solution suggested by Stevens (1951), wherein the sensitivity matrix (the covariance matrix in this case) depends upon the estimate of R, is employed. The program then uses the following stopping condition:

If $\frac{|R(k-1)-R(k)|}{1-R(k)} < 10^{-5}$, then STOP

Otherwise, continue with iteration k+1.

The resulting estimates of model parameters for each subject's tracking error are presented in Table 5. The "late training" average scores (treated in Section 4.2.1) are tabulated as well, and are seen to reasonably agree (well within a standard deviation) with the estimates for asymptotic performance across groups.

A planned CRF ANOVA was conducted for each of the model parameters. In addition it was decided to conduct a CRF ANOVA on the model's estimate for initial performance. These results are shown in Tables 7 through 10 for asymptotic performance Y_A, learning rate R, amount of tracking error change B, and initial performance Y(1), respectively.

The result of the ANOVA on asymptote means (Table 7) is nearly identical to that found when comparing average "late training" performance. The strength of association of the effect is the same, i.e., 92% of the variance was accounted for by "Drive Law." One difference detected among asymptote means which is not significant in the "late training" tests is the difference between performance for the POSITION and VELOCITY groups (see the Tukey Test for Factor A). The differences in the estimates for asymptotic performance and the "late training" averages are sufficient to move this comparison from below the threshold of detection into the "detectable difference" category (in both tests the critical differences are nearly identical). It is clear that performance with the Position Drive Law is not as good as that obtained with the Velocity Drive Law. However, it is equally clear from the magnitude of the STATIC-POSITION difference that the Position Drive Law provided useful motion information.

A weak (1% strength of association), though significant, main effect of Sex (Factor B) is also apparent. The Tukey Comparison shows a lower tracking error for males—on the order of 0.5 deg. A plausible explanation may be found in the later discussions of the frequency domain variables (Section 4.3.2), where it will be seen that the males tracked with a higher gain (i.e., applied a higher force to the controller per degree error) than did the females.

There are no detectable differences in learning rates across training conditions or sex (Table 8). This variable shows a relatively large within cell variability, which suggests that individual differences such as natural ability and motivation played the major role in affecting the rate of learning. (The critical difference, assuming a main Drive Law effect, would be 0.09.)

The amount of tracking error change over all training trials, model parameter "B," shows no effect of Drive Law (Table 9). A significant main effect of Sex was detected, however, with a strength of association accounting for 23% of the variance. According to the Tukey Test, the males show an improvement in tracking error which is 2.3 degrees less than that of the females. Since the males' asymptotes averaged 0.5 degrees below that of the females, the expected initial score Y(1) for the males should be about 2.8 degrees lower than that for the females. This is in fact the case, as results of the next test indicate.

It was decided to include a test on the asymptotic model's estimate for initial tracking performance in order to obtain a look at the combined effects of Y_A and B. The effect of the different training environments on initial performance may, in itself, be of general interest. Model estimates of initial performance are obtained by summing the values for parameters Y_A and B (see Equ.(4-1)), which are available in Table 5. The results of the ANOVA (Table 10) reveal a main effect of both Drive Law and Sex, with a 33% strength of association for Drive Law and a 23% strength of association for Sex. The Tukey Test for Drive Law detected a significant difference only between the STATIC and MOTION groups. No significant differences exist between the MOTION and either dynamic seat group. The 3.15 degrees critical difference is rather large, however. If one looks at the trends in the pairwise comparisons, it is observed that initial performance for the two dynamic seat groups is rather close (0.52 degrees), and that the initial tracking errors lie roughly midway between those of the STATIC and MOTION groups. The lowest initial tracking scores are obtained for the MOTION group. The difference in performance seen for “Sex” has already been inferred from previous tests, namely those on the individual model parameters Y_A and B. The male-female difference in initial performance was largely compensated by the females’ greater improvement with training (Table 9). The residual shows up as a difference in asymptotic performance between males and females (Table 7).

4.2.3 Discussion of the Results of Comparisons of Tracking Error Performance During Training

It is clear from the “late training” results that motion information provided by the dynamic seat is sufficient to elicit tracking performance equivalent to that obtained in the whole-body motion environment. The Position Drive Law was not as effective as the Velocity Drive Law in this respect, but still provided results significantly better than the static case.

The results of the tests on the asymptotic model parameters indicated a main effect of sex on initial performance, asymptotic performance, and the amount of tracking error reduction with training. These results indicate that the females did poorer initially, but improved more than the males did with training. The resulting asymptotic performance still showed an association, albeit very weak, between sex and tracking error. There is probably no practical significance to this (less than 0.5 degrees) asymptotic performance difference—in fact, no statistically significant difference was detected in the comparison of average “late training” scores.

The ANOVA of the asymptotic model’s learning rate parameter detected no significant effect of Drive Law. Hence the presence, or absence, of motion information did not affect the rate of tracking error skill development in this experiment.

4.2.4 Tracking Error at Transition

Attention is now turned to investigating how well the tracking skill developed during the 80 training runs carried over to the whole-body motion environment. This section will focus upon tracking performance transition from the last training run to the first whole-body motion run.

In this section, a planned ANOVA using a Split Plot Factorial (SPF) design is used to test for differences in tracking errors across runs 80 and 81. There are four levels of “Drive Law” (Factor A), two levels of “Sex” (Factor C), and two levels of “Runs” (Factor B). In this case the subjects (blocks) within each group receive only one level of A and C, but both levels of B. The SPF design is appropriate for this mixed analysis of two between block factors and one within block factor. Because there may be interest in the absolute change in the mean group performance at transition, the Run 80-Run 81 pairwise difference is reported in the Tukey Test Table for Factor B Means even when the ANOVA did not indicate significance (in this case the pairwise difference is annotated as “reference only”).

The ANOVA results are presented in Table 11. The significant main effect of “Drive Law” is seen to have a strength of association of 64%. However, a significant “Drive Law” by “Run” (AB) interaction is indicated. The procedure recommended by Kirk (1968) in this case is to conduct simple main effects tests with the per family error rate controlled at the same level as that of the overall F test. That is, the overall level of $p=.05$ for main effects tests is divided evenly among a collection of simple main effects tests.

The “Significant AB” ANOVA in Table 11 shows a significant simple main effect of “Drive Law” at both levels of “Run” ($p=.05/2=.025$). Further, there is a significant simple main effect of “Runs” for all levels of “Drive Law,” excepting MOTION ($p=.05/4=.0125$).

Since the overall ANOVA also detected a significant—although weak (1% strength of association)—“Runs” by “Sex” (BC) interaction, a “Significant BC” ANOVA was also conducted. This ANOVA found a significant simple main effect of “Runs” for males ($p=.05/2=.025$). No other simple main effects are significant for this interaction.

The Tukey Multiple Comparison Test results in Table 11 are for tests conducted for each significant simple main effect.

The pairwise comparisons for the simple main effect of “Drive Law” at “Run 80” show tracking error performance differences between groups very close to those seen in Table 6 (“late training” average scores) and in Table 7 (asymptotic tracking error scores). In fact, if the critical difference were as sensitive in this test as in Table 7, the results would have been equivalent.

This particular test does not provide any new information regarding the effects of drive law on asymptotic tracking performance, but it does indicate that tracking performance at Run 80 was typical of performance late in training.

The Tukey Test for the simple main effect of “Drive Law” at “Run 81” does yield new information. These results show that there is no significant difference in the performance of the STATIC trained group from that of the POSITION or VELOCITY trained groups. That is to say, training with seat cues did not significantly improve initial tracking performance in the criterion motion environment above that obtained with STATIC training. Further, all three groups performed significantly worse than MOTION subjects with a like amount of training.

The Tukey Comparisons for the simple main effect of “Run” at the STATIC, POSITION, and VELOCITY levels of “Drive Law” show the change in average tracking performance as the groups transitioned from Run 80 to Run 81. There is one pairwise comparison at each level of “Drive Law.” Each pairwise difference for the STATIC, POSITION, and VELOCITY groups is significant. The STATIC group’s performance change was in the direction of better performance, whereas the POSITION and VELOCITY groups did more poorly.

The Tukey Comparison which was conducted for “Runs” at the male level of “Sex” as a result of the “Significant BC” ANOVA did not find a significant difference. This effect was not strong enough to be detected with the Studentized Range statistic used in the Tukey Test at $p=.05/2=.025$ (corresponding to a critical difference of 0.56 degrees). Although the effect was significant in the “Significant BC” ANOVA, its association with the dependent variable was so weak (1%) that the statistical significance was, in any event, of little practical significance.

After observing how the POSITION and VELOCITY subjects fared in their first whole-body motion run, it became questionable whether any training benefit was derived from the 80 training runs. It was therefore decided to conduct an additional, unplanned ANOVA comparing the Run 81 tracking performance of the STATIC, POSITION, and VELOCITY trained groups to the MOTION group performance at Run 1 in order to determine whether there was any significant performance advantage gained by the training. In this case there are two between block factors, “Drive Law” (Factor A) and “Sex” (Factor B). An appropriate design is the Completely

Randomized Factorial (CRF) ANOVA (Kirk, 1968), the results of which are shown in Table 12. No significant effects were detected. (The Tukey critical difference for testing the main effect of “Drive Law” would have been 2.6 degrees.)

In sum, the tests of this section found no significant training benefit of dynamic seat cues relative to the STATIC training condition. Further, the results show that subjects trained under STATIC, POSITION, or VELOCITY conditions did not do significantly better upon transition to the criterion motion environment (after 80 training runs) than did the naïve subjects in their initial MOTION training run.

<u>4.2.5 Post-transition Tracking Error</u>

This section deals with performance across the post-transition sessions. It was anticipated that tracking performance might differ among the four groups following transition to the whole-body motion environment. Under such conditions, it is often interesting to know when the differences disappear. To address this issue, it was planned to conduct a Split Plot Factorial (SPF) ANOVA comparing tracking scores over four post-transition sessions (four runs to a session). Average performance scores for sessions 21, 24, 27, and 30 (which provide data for early, mid, and late post-transition tracking spread over equal intervals) are the dependent variables. The number of sessions considered was limited to four in order not to unduly dilute the sensitivity of the tests.

The resulting SPF-42.4 has one within block factor “Sessions” (Factor B), and two between block factors “Drive Law” (Factor A) and “Sex” (Factor C). The results appear in Table 13. A significant main effect of “Drive Law” and of “Sessions” is indicated, with a strength of association of 19% for “Drive Law” and 38% for “Sessions.” Since there is also a significant “Drive Law” by “Sessions” interaction (with a 14% strength of association), the next step is to look at the simple main effects (Kirk, 1968). The “Significant AB” ANOVA table reveals a significant simple main effect of “Drive Law” at session 21 (B1) and at session 24 (B2) ($p=.05/4=.0125$). Thereafter, the differences are not significant. Significant simple main effects of “Sessions” exist for all levels of “Drive Law,” excepting MOTION ($p=.05/4=.0125$).

The Tukey Pairwise Comparisons in Table 13 for "Drive Law" at session 21 show that the STATIC, POSITION, and VELOCITY groups all tracked significantly more poorly than the MOTION group. No significant differences are observed for performance differences between the STATIC, POSITION, or VELOCITY groups.

The Tukey Test for "Drive Law" at session 24 did not find any pairwise differences greater than the 0.85 degrees critical difference. Although the "Significant AB" ANOVA indicated there was a difference in mean tracking scores among the four "Drive Law" groups at the p=.05/4=.0125 confidence level, the difference was not great enough to be detected with the Studentized Range statistic used in the Tukey Test. This result suggests that by session 24, for all intents and purposes, all groups were operating at the same level of performance.

A significant "Sessions" effect indicates that there is some continued learning (or skill development) going on at those levels of "Drive Law" for which "Sessions" is significant. The level B1-B4 difference (the Session 21-Session 30 difference in this case) indicates what the total change was across sessions. Other "Session" level differences merely provide information regarding the shape of the learning curve. For example, the Tukey Test for "Sessions" at the POSITION level of "Drive Law" in Table 13 shows no change in performance following session 24 greater than the 0.46 degrees critical difference. The STATIC and VELOCITY groups still show a significant change in performance between sessions 24 and 30, but none between sessions 24 and 27 or sessions 27 and 30. These results indicate that the POSITION group's skill development had essentially leveled out by session 24; whereas the STATIC and VELOCITY groups were still improving—but at a rate significantly reduced from that observed in the session 21 to 24 difference. The trends exhibited by all three of these groups are similar. <u>The major improvement in tracking performance takes place by the end of session 24</u>, and then continues to gradually approach some plateau level in an exponential-like way.

After noticing the similarities in the shape of the post-transition curves of the STATIC, POSITION, and VELOCITY groups (Fig. 21, Fig. 22, and Fig. 23) and the training curve for the MOTION group (Fig. 24), it was decided to conduct an ANOVA identical to the SPF-42.4 of Table 13—but with the MOTION scores for sessions 21, 24, 27, and 30 replaced with the MOTION scores for sessions 1,4, 7, and 10. The intent here was to see whether any benefit of training under STATIC, POSITION, or VELOCITY conditions appeared. The ANOVA results are presented in Table 14. No effect of "Drive Law" is seen (the critical difference corresponding to a simple main effect of "Drive Law" would be 1.3 degrees). Only the main effect of "Sessions" is significant. This was seen for all groups—whether trained under STATIC, POSITION, or VELOCITY conditions for 80 runs, <u>or with no previous training at all</u>.

<u>4.2.6 Discussion of the Results of Comparisons of Transition and Post-transition Tracking Error Performance</u>

It is evident from the results of Section 4.2.4 that training in the dynamic seat did not materially improve initial whole-body tracking performance above that achieved by training in a static (i.e., visual cues only) environment. Further the CRF-42 test results of Table 12 suggest that training in either a static environment or dynamic seat cuing environment did not suffice to teach subjects to use the information which would be available to them in a full motion environment. These results were reinforced by the test results reported in Section 4.2.5, where tracking scores across post-transition sessions were analyzed. No substantial improvement in post-transition tracking was observed as a result of static or dynamic seat training. A simple main "Sessions" effect indicated that significant post-transition skill development was occurring for the STATIC, POSITION, and VELOCITY groups (Table 13). In fact, no significant tracking differences were observed when the performance of "well trained" (80 runs) members of the STATIC, POSITION, and VELOCITY groups was compared to that of naïve members of the MOTION group (Table 14); a main effect of "Sessions" was found, indicating only that skill development was proceeding for all four groups.

4.3 Frequency Domain Measures of Control Behavior

The four frequency domain variables which will be used to test for differences in control behavior (Appendix E) are the open loop man-vehicle crossover frequency (ω_C), gain (K_L), phase margin (φ_M), and the slope of the open loop gain curve in the vicinity of crossover (rolloff). Point estimates for each of these variables were obtained for each run, as explained in Chapter 3.

Figs. 25 through 40 show how these variables changed over the course of the experiment. The figures show a general tendency for each of these variables to level out at some plateau late in the training phase, and then again late in the post-transition phase of the experiment. An examination of the MOTION group's scores shows that ω_C, φ_M, and K_L continue to progress toward some plateau following run 80. Since the tracking environment did not change for the MOTION group at transition, this is an indication that more than 80 training runs were required to attain asymptote along these dimensions. However, the trends in the figures do not suggest that asymptotic levels would be radically different from the levels attained at the end of 80 training runs.

In Section 4.2 we were interested in comparing group scores on the basis of how well subjects performed their assigned task. In this section, we want to determine how the different groups modified their control behavior in order to perform the task. The four frequency domain "crossover scores" (ω_C, φ_M, K_L, and rolloff) are the dependent variables used to test for control behavior differences among groups. The same procedures were followed for the "crossover scores" as were for the tracking error scores, with the exception of tests on asymptotic model parameters. As mentioned elsewhere (Section 4.1), the large number of instances of lack-of-fit (as defined by the Appendix C criteria) made it unreasonable to expect that unbiased model parameter estimates would be obtained using available data.[6]

As in the case of tracking error, "late training" crossover scores averaged over runs 65 through 80 for each subject are compared in order to test for control behavior differences in the training environment. In addition, the four crossover scores are shown to capture the essence of the linear portion of the human operator describing function.

Control behavior differences at transition are examined by comparing the crossover scores over runs 80 and 81, the last training and first post-transition runs respectively.

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[6] The specific criterion violated in every instance was that associated with the asymptote being insufficiently defined within the scope of the data.

Post-transition control behavior is tested by comparing the crossover scores over sessions 21, 24, 27, and 30—as was done for tracking performance.

4.3.1 Control Behavior Late in Training

Control behavior during "late training" is characterized for each subject in terms of the four crossover scores averaged over runs 65 through 80.

In order to first demonstrate that the estimates for the crossover scores do represent the data, the open loop describing functions' gain and phase data are presented with the crossover score averages superimposed. These data are shown in Figs. 9 through 12 for the STATIC, POSITION, VELOCITY, and MOTION groups, respectively. Each describing function data point is the average of all valid estimates for that subject over runs 65-80. The superimposed crossover scores are averaged across all sixteen "late training" runs and all six subjects in the group (96 estimates are included in each average). Mean values and standard deviation bars are shown for ω_C, K_L, and the phase angle corresponding to φ_M. The line faired through the gain data has the mean "rolloff" slope. (The standard deviations associated with the "rolloff" slope averages are not provided on the curves. These are 1.9, 1.4, 1.8, and 1.3 db/decade, for the STATIC, POSITION, VELOCITY, and MOTION groups respectively.) As explained in Section 3.5, K_L and "rolloff" were jointly estimated using a linear least square fit to the gain data in the frequency range between 1.0 and 5.7 rad/s. Estimates for ω_C and φ_M were obtained by linearly interpolating between the describing function estimates on either side of crossover, and so were estimated independently of K_L and "rolloff." It is evident from these figures that the averaged crossover scores do reasonably represent the data. (These fits are typical of what was obtained on a run-by-run basis, although an individual run was liable not to have had as many valid describing function point estimates as do these averages—particularly early in training.)

The "late training" crossover scores are compared using a planned Completely Randomized Factorial (CRF) ANOVA with four levels of "Drive Law" (Factor A) and two levels of "Sex" (Factor B). The results are in Tables 15, 16, 17, and 18 for ω_C, φ_M, K_L, and "rolloff" respectively.

The effective time delay τ_E is a popular summary statistic appearing in numerous reports regarding the effects of motion information in manual tracking tasks. Although not employed as a principal metric in this experiment (for reasons stated in Appendix E), a supplemental CRF ANOVA of τ_E is included in this section (Table 19) so that these results can be more readily related to the existing literature. τ_E was calculated using Equ.(E-4) and ω_C, φ_M, and "rolloff" data from Tables 15, 16, and 18. "Rolloff" was normalized by 20 db/decade in order to obtain the appropriate values for the gain slope parameter N.

The results for ω_C (Table 15) are seen to parallel those for "late training" tracking error (Table 6). There is a significant main effect of "Drive Law" with a 73% strength of association. The Tukey Test (bottom of Table 15) shows that the STATIC group was operating with a crossover frequency (and, hence, effective man-vehicle bandwidth) significantly lower than that of all the other groups. The POSITION group's ω_C was significantly below that of the MOTION group. However, the VELOCITY group's ω_C was not detectably different from that of the MOTION group. (The Tukey Test critical difference is 1.14 rad/s, with the error rate for the family of pairwise comparisons controlled at p=.05.)

The ANOVA of φ_M (Table 16) shows a significant main effect of "Drive Law" (28% strength of association) and of "Sex" (12% strength of association). The only significant pairwise comparison found in the Tukey Test for "Drive Law" was that between the STATIC and MOTION groups, with the MOTION group operating at 10 degrees lower phase margin than the STATIC group. (The critical difference for the Tukey Test for "Drive Law" is 8.3 degrees.) The Tukey Test for "Sex" indicated that the males were operating at about 5 degrees lower phase margin than the females; the critical difference for this test is 4.3 degrees.

The ANOVA of K_L (Table 17) also shows a significant main effect of "Drive Law" (87% strength of association) and of "Sex" (2% strength of association). The Tukey Test results for "Drive Law" exactly parallel those of the tests for ω_C (Table 15) and "late training" tracking error (Table 6). That is, the STATIC group was operating at a significantly lower gain than the other groups, and the POSITION group was operating at a gain lower than that of the MOTION group.

No detectable gain difference exists between the VELOCITY and MOTION groups. (The detectable difference for “Drive Law” is 2.4 db.)

The ANOVA of “rolloff” (Table 18) indicates a significant main effect only for “Drive Law” (86% strength of association). The Tukey Pairwise Comparisons show that the STATIC group was operating at a significantly shallower “rolloff” than were the other groups. No differences were detectable for “rolloff” between the POSITION, VELOCITY, or MOTION groups. (The critical difference is 1.9 db/decade.)

The ANOVA results for the composite metric τ_E (Table 19) indicate a significant main “Drive Law” effect with a strength of association of 90%. The Tukey Test showed that the effective time delay for the STATIC group is significantly greater than that for the other groups. No other pairwise comparisons are significant. (The critical difference is .061 seconds.) This result is consistent with the significantly lower crossover frequency and “rolloff” scores observed for the STATIC group relative to the others.[7]

4.3.2 Discussion of the Results of Comparisons of the “Late Training” Crossover Scores

The preceding results demonstrate that broad area, seat pan tactual cues can effectively provide motion information which elicits control behavior equivalent to that observed in a whole-body motion environment (for control behavior measured in terms of crossover frequency, phase margin, low-frequency open-loop gain, and open-loop gain rolloff). Specifically, it was shown that subjects performing a roll-axis disturbance regulation task with motion information provided through a seat pan (using a Velocity Drive Law) adopted a control behavior equivalent to that adopted by trackers in a whole-body motion environment—as measured along the four “crossover” dimensions and in terms of effective time delay. The Position Drive Law was not as effective as the Velocity Drive Law, but still demonstrably better than visual cues alone (i.e., STATIC).

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[7] A first-order Taylor series expansion about a nominal value of τ_E computed from the grand means of ω_C, φ_M, and “rolloff” (see Appendix B in Eveleigh, 1967) indicated that the sensitivity of τ_E to observed changes in φ_M was less than that to observed changes in either ω_C or “rolloff.”

The results are generally consistent with the adjustment rules associated with McRuer's Crossover Law (e.g., Jex, 1971; McRuer and Jex, 1967). That is, the trackers adopted the necessary control equalization such that they could adopt a high low-frequency gain (in order to provide good closed loop low-frequency response for disturbance suppression) with an open loop gain "rolloff" of approximately –20 db/decade over a wide frequency range near the crossover region. As one would expect, the tracking error (disturbance regulation) performance is correlated to higher low-frequency gain. In this case, the significant "Drive Law" pairwise comparisons observed for tracking error occur for the same treatment level pairs as in the comparisons of gain.

A significant main effect of "Sex" was detected for gain. Although this may not have a great deal of practical significance due to its negligible (2%) strength of association, it does indicate a correlation—however trivial—between sex and gain. This suggests that there may be a physiological basis for the weak (1% strength of association), but statistically significant difference found in tracking error asymptotes (Section 4.2.2) for the two levels of "Sex". That is, the males were found to have a lower asymptotic tracking error, which could be accounted for by their higher low-frequency gain (i.e., the males, on the average, applied a higher force to the controller per degree error).

The males operated with a higher low-frequency gain and significantly lower phase margin (Table 16) than the females. However, no statistically significant difference in crossover frequency (the males averaged about 0.6 rad/s higher than the females) or in "rolloff" (the males operated at about 0.5 db/decade steeper slope) was found due to "Sex."

The phase margin data show a significant difference between the STATIC and MOTION conditions. Although other differences are not significant, it is clear from both the figures (Fig. 29 through 32) and the Tukey Pairwise Comparisons (Table 16) that the phase margins of the POSITION and VELOCITY groups more closely resemble that of the MOTION group than that of the STATIC group. Reductions in phase (stability) margins with the addition of useful motion are seen elsewhere in the literature for similar tasks (Jex et al., 1981; Ringland and Stapleford, 1971).

A significant association between "Drive Law" and "rolloff" is indicated. It is seen that the STATIC group was operating very close to the –20 db/decade "rolloff" which is widely reported in the manual control literature (e.g., McRuer and Jex, 1967). The "rolloff" for the POSITION, VELOCITY, and MOTION groups is somewhat sharper, however, averaging about –26 db/decade. This phenomenon is not widely reported per se, but similar tendencies for similar tasks have appeared in the literature (Hosman and van der Vaart, 1981). A hypothesis for this effect is that the operator is using the motion information to close additional inner loops (Jex et al., 1981; Levison et al., 1984; McMillan et al., 1984), which in turn are introducing higher order effects in the vicinity of crossover. The data collected in this experiment are not sufficient to test this hypothesis as this was not an objective of the experiment. (Additional data are required to identify the separate visual and motion pathway dynamics in the human operator (Jex et al., 1981).) Of direct relevance to the experimental objectives is the fact that there were no significant differences in the "rolloff" means adopted by the POSITION, VELOCITY, or MOTION groups. On the other hand, the STATIC group's mean rolloff was significantly different from that of the other groups.

Jex et al., (1981) determined that motion cues in a disturbance regulation task similar to that used in this experiment permitted a "roll-rate damper" loop to be closed by the operator—enabling higher crossover frequencies, greater loop gains, and lower lags. That interpretation was concluded to be consistent with, and provide insight into, the findings of Shirley (1968) and Stapleford et al., (1969). Equivalent motion cue effects are evident in the results of this experiment. <u>In addition to higher loop gains</u> (and crossover frequencies), <u>motion information</u>—whether displayed by the dynamic seat or RATS cab—<u>resulted in effective time delay reductions of 0.21 to 0.27 seconds</u> relative to the STATIC group.

4.3.3 Correlation of the Crossover Scores to the "Late Training" Human Operator Describing Functions

It is postulated that, because the differences between the VELOCITY and MOTION groups' scores for ω_c, φ_M, K_L, and "rolloff" are not significantly different with controlled plant dynamics (Chapter 2) held constant, the subjects in these groups must be utilizing available motion information to develop control equalization strategies which are equivalent. This argument is further supported by similarities in the human operator describing functions.

Fig. 13 through Fig. 16 show the human operator describing function estimates obtained for the STATIC, POSITION, VELOCITY, and MOTION groups respectively. Each data point is averaged over sixteen runs, and across the six members of each group. Plotted side-by-side are the data for runs 65-80 (“late training”) on the left, and runs 105-120 (“late post-transition”) on the right. The “late post-transition” describing functions are similar for all groups, suggesting a reasonable match across groups in terms of control styles adopted after some experience in the full motion environment.

The “late training” data for the VELOCITY and MOTION groups (left side of Fig. 15 and 16) virtually overlay. The gain and phase estimates on one figure are within a standard deviation of those on the other. The only observable difference of any consequence is in the area of mid-frequency remnant, where the VELOCITY group remnant is high enough that the standard deviation bars do not overlap with those of the MOTION group. Perceptual and signal processing noise is an important source of remnant (Jex, 1971; Kleinman et al., 1969; Kleinman et al., 1971; Levison, 1983; Levison et al., 1976; Zacharias and Levison, 1979), so it is reasonable to suspect that this may be related to the quality of the motion information relayed by the seat. This possibility is pursued later. Since the linear portions of the describing function data (i.e., the gain and phase) do match reasonably well, the members of both groups have evidently adjusted their control behavior for similar gains and lead equalization. This is consistent with there being no statistically significant differences between the VELOCITY and MOTION crossover scores.

When the POSITION group’s describing function (Fig. 14) is compared to that of the MOTION group, observed differences in the gain and lead equalization become more pronounced. The POSITION group’s phase lead begins to drop off substantially (relative to that of the MOTION group) above 3 rad/s. With less high frequency phase lead compensation and no substantial difference in phase margin, the crossover frequency (and hence low-frequency gain) must be lower in order to maintain closed-loop stability. This is consistent with the POSITION-MOTION differences found in the Tukey Tests on the crossover scores.

The STATIC group's describing function (Fig. 13) shows no phase lead compensation, and a (consequently) markedly reduced low-frequency gain. Again, this is consistent with the observed crossover score differences.

To summarize, where observed crossover scores were similar, so were the human operator describing functions. As one moves in the direction of reduced effectiveness of the displayed motion information in terms of the crossover scores, one observes the corresponding reduction in the human operators' high-frequency lead equalization and attendant reduction in low-frequency gain in the describing function. The crossover scores appear to be reasonably effective in capturing the differences in control behavior, and are employed from this point forward without recourse to qualitative evaluations of human operator describing functions.

There is corroboration in the literature for the STATIC and MOTION describing functions obtained. Levison (1983), Levison et al., (1979), and Levison and Junker (1977) show similar "fixed base" and "moving base" characteristics for operators tracking with a like set of task variables.

The aforementioned differences in closed-loop remnant observed between the VELOCITY and MOTION groups provided motivation to investigate the open-loop remnant of all the groups. Levison et al., (1969) note that the most stable representation is obtained by referring remnant to an equivalent observation noise source. They further show that if this observation noise spectrum is normalized with respect to error variance, the result is relatively insensitive to the characteristics of the forcing function. The assumption is made that the residual remnant component, due mainly to accumulated thresholds in the perceptual-motor system, can be neglected (Jex, 1971). If, in addition, it is assumed that no nonlinearities are passed in the process, then the normalized remnant-related observation noise spectrum can be calculated using the following relationship adapted from McRuer et al., (1965).

$$\Phi_O(\omega) = \frac{\left|1 + HV(j\omega)\right|^2 \bullet \Phi_R(\omega)}{\left|H(j\omega)\right|^2 \bullet \mathrm{var(error)}} \quad \text{...(4-3)}$$

$\Phi_R(\omega)$ is the measured component of the operator's output not linearly correlated with the input, $\Phi_O(\omega)$ is the normalized open-loop remnant referred to the operator's input, and var(error) is the error variance. The two alternative conceptualizations of remnant are illustrated in Fig. 8. $\Phi_O(\omega)$ has the dimension of one over frequency, $(\text{rad/s})^{-1}$; zero db corresponds to one $(\text{rad/s})^{-1}$. $H(j\omega)$ and $HV(j\omega)$ are defined by Equ.(3-1) and Equ.(3-3) respectively. The human operator describing functions of Fig. 13 through 16 are repeated in Fig. 17 through 20, but with the stochastic portion now being $\Phi_O(\omega)$ rather than $\Phi_R(\omega)$.

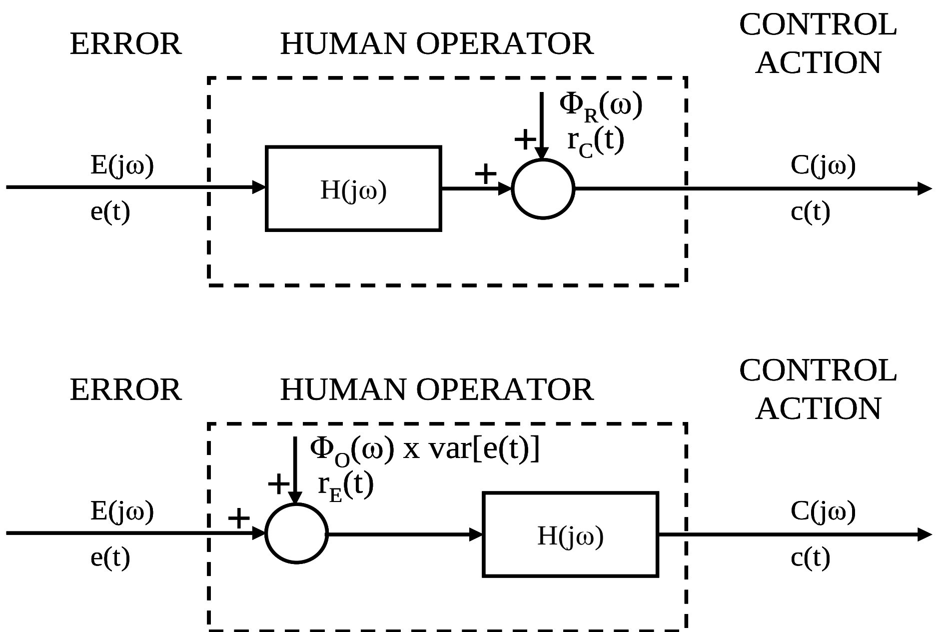

Figure 8. Two alternative representations of Human Operator Remnant (after Jex, 1971)
The upper HUMAN OPERATOR block, from Fig. 1, shows remnant referred to the operator's output. The lower HUMAN OPERATOR block illustrates remnant referred to the operator's input as an equivalent observation noise source which scales with the displayed error variance, var[e(t)].

$e(t)$ or $E(j\omega)$ = System Error
$c(t)$ or $C(j\omega)$ = Operator's Control Action
$r_E(t)$ or $\Phi_O(\omega)$ = Operator Remnant Referred to Input
$r_C(t)$ or $\Phi_R(\omega)$ = Operator Remnant Referred to Output
$H(j\omega)$ = Operator Describing Function

The "late training" $\Phi_O(\omega)$ spectra for the STATIC, POSITION, and MOTION groups (the left sides of Fig. 17, 18, and 20) are virtually indistinguishable; all the standard deviation bars are observed to overlap. (Since the RATS model following drive law did not hold up well above 11 rad/s (see Table 2), and high frequency cab motion was therefore inappropriate, it is not clear that any practical significance should be attributed to the slightly greater high-frequency remnant power exhibited by the MOTION group.) The input-correlated response of the VELOCITY group during "late training" (the GAIN and PHASE on the left side of Fig. 19), is seen to be practically identical to that of its MOTION counterpart. However, it is observed that the Velocity group was operating with a somewhat higher remnant power than the other groups out to just beyond 3 rad/s. This suggests that the VELOCITY group was having some difficulty in picking up and properly interpreting the mid-frequency motion information provided by the dynamic seat, and was consequently injecting more power at non-input frequencies over this frequency range. This interpretation is consistent with the model predictions of Zacharias and Levison (1979) for higher "position observation noise" levels. The implication is that the Velocity Drive Law may be interfering with the pick-up of position information. The converse problem (i.e., higher "rate observation noise" levels) is not evident in the POSITION group's remnant spectrum. On the other hand, the POSITION group's phase characteristic correlates well with the MOTION group's only over the lower frequencies—out to about 3 rad/s. (The low- frequency gain characteristic was lower by necessity because the POSITION group was not generating sufficient high-frequency phase lead to permit higher gain levels without sacrificing stability.)

In sum, The POSITION remnant spectrum agrees with that of the MOTION group at all frequencies, whereas that of the VELOCITY group agrees well only above 3 rad/s. The phase characteristic of the VELOCITY group agrees with the MOTION group's overall, whereas that of the POSITION group falls off above 3 rad/s. These phenomena suggest that <u>a more optimal "Drive Law"</u> (in terms of a better match of both the linearly correlated and the stochastic portions of the describing function to the full motion situation) <u>would be one which looked like the POSITION "Drive Law" at low frequencies, and the VELOCITY "Drive Law" at higher frequencies</u>. The data suggest that this transition occur in the neighborhood of 4 rad/s.

4.3.4 Control Behavior at Transition

Crossover scores obtained at run 80 (the last training run) and run 81 (the first whole-body motion run) were tested to determine how control behavior carried over from training to the full motion environment. This resulted in two between block factors, “Drive Law” (Factor A) and “Sex” (Factor C), and one within block factor “Runs” (Factor B). The planned ANOVA appropriate for this mixed analysis is the Split Plot Factorial (Kirk, 1968). The SPF ANOVA results are presented in Tables 20 through 23 for ω_C, φ_M, K_L, and “rolloff” respectively.

The ANOVA results of ω_C (Table 20) show a significant main effect of “Drive Law” (57% strength of association) and a significant “Drive Law” by “Run” interaction (5% strength of association). Due to the interaction, a “Significant AB” ANOVA is conducted next to test for simple main effects (Kirk, 1968). There is a simple main effect of “Drive Law” at both levels of “Run” (p=.05/2=.025). No simple main effect of “Runs” is detected (p=.05/4=.0125). That is to say, no significant difference in ωC is observed in going from Run 80 to Run 81 at any level of “Drive Law,” while controlling the error rate at p=.05.

The Tukey Pairwise Comparisons for the simple main effect of “Drive Law” at Run 80 (Table 20) indicate a significant difference only between the STATIC-VELOCITY and STATIC-MOTION pairs (the critical difference is 1.69 rad/s). This is not the same result as obtained in the tests of “late training” data (Table 15). However, an examination of the pairwise differences suggests that this lack of agreement stems from different sensitivities in the two tests rather than any marked anomalies in the differences obtained at Run 80 alone versus the “late training” averages. It does not appear that the Run 80 data are atypical.

The Table 20 pairwise comparisons of ω_C means at Run 81 (with a critical difference of 1.69 rad/s) detect only one significant difference for the simple main effect of “Drive Law,” that between the STATIC and MOTION groups. Although the POSITION-MOTION and VELOCITY-MOTION differences were not significant, neither were the STATIC-POSITION or STATIC-VELOCITY differences.

The results of the ANOVA of φ_M (Table 21) reveals a significant main effect of “Drive Law” (31% strength of association). No significant effect of “Runs” is observed; that is, all groups transitioned with a relatively constant phase (or stability) margin.

The Table 21 Tukey Pairwise Comparisons of “Drive Law” φ_M means show a significant difference between the STATIC group and the other three groups. No significant differences are observed between the POSITION, VELOCITY, or MOTION groups (the critical difference is about 10 degrees). This is consistent with the trends seen for “late training” φ_M (Table 16).

The ANOVA of K_L (Table 22) reveals a significant main effect of “Drive Law” (68% strength of association) and a significant “Drive Law” by “Run” interaction (11% strength of association). The “Significant AB” ANOVA shows a significant simple main effect of “Drive Law” at both levels of “Run” (p=.05/2=.025). The significant simple main effect of “Runs” for the STATIC and VELOCITY levels of “Drive Law” (p=.05/4=.0125) indicates that these two groups changed their gains significantly upon transitioning to the criterion whole-body motion device.

The Table 22 Tukey Pairwise Comparisons for “Drive Law” at Run 80 (with a critical difference of 3.74 db), replicated the results seen for “late training” K_L (Table 17). This is indicative of Run 80 consistency with the average “late training” gain. The Pairwise Comparisons for “Drive Law” at Run 81 reveal significant gain differences only between the MOTION group and the other three groups. No significant differences in gain are observed between the STATIC, POSITION, or VELOCITY groups at Run 81.

The ANOVA of “rolloff” (Table 23) shows a significant main effect of “Drive Law” (37% strength of association) and a significant “Drive Law” by “Run” interaction (20% strength of association). The “Significant AB” ANOVA indicates a simple main effect of “Drive Law” at both levels of “Run” (p=.05/2=.025) and of “Runs” only for the STATIC level of “Drive Law” (p=.05/4=.0125). This latter result is evidence that only the STATIC group’s “rolloff” changed significantly at transition.

The Pairwise Comparisons for “Drive Law” at Run 80, with a critical difference of 4.57 db/decade, replicated the results seen for “late training” “rolloff” (Table 18). Again, this demonstrates Run 80 consistency with the "late training" data. The only significant pairwise difference at Run 81 is seen to be that between the POSITION and MOTION groups. It turns out that the STATIC group modified its behavior to the extent that its slope was more similar to that of the MOTION group at Run 81 than was that of either the POSITION or VELOCITY group. It was this relatively large change in the STATIC group's "rolloff" slope that accounts for the significant simple main effect of "Runs."

As was the case with tracking error, there appeared to be a great deal of similarity between the crossover scores obtained post-transition for the STATIC, POSITION, and VELOCITY groups and the initial training scores for the MOTION group (Fig. 25 through 40). An unplanned set of ANOVA, comparing Run 81 crossover scores for the STATIC, POSITION, and VELOCITY trained groups to Run 1 MOTION group scores, was therefore carried out to see whether any detectable differences would be found as a result of training. Since only two between block factors ("Drive Law" and "Sex") were involved, a Completely Randomized Factorial (CRF) ANOVA was used. The results of the ANOVA on ω_C, φ_M, K_L, and "rolloff" are in Tables 24 through 27.

No significant differences are observed for either ω_C or "rolloff."

A significant main effect of "Drive Law" is detected in the ANOVA of φ_M (Table 25), with a 27% strength of association. No significant difference is detected in the Tukey Test however (the critical difference is 17.5 degrees).

A significant main "Drive Law" effect is observed for gain (Table 26). In this case a significant pairwise VELOCITY-MOTION difference appears (with a 5 db critical difference).

In reviewing the results of the Run 80-Run 81 transition tests, some salient points emerge.

It was found that the different groups retained their respective stability margins, φ_M, upon transferring from their training conditions to the full motion environment. It is observed that dynamic seat training did help subjects learn to track with reduced stability margins (6 to 10 degrees lower than the STATIC group), and that this carried over to the whole-body motion environment.

The advantage of dynamic seat training was more equivocal with respect to gain, K_L. The STATIC group was tracking with a significantly lower gain than the dynamic seat groups late in training. However, these differences disappeared upon transition—whereupon the STATIC gain increased significantly, while the VELOCITY gain (and to a lesser extent, the POSITION gain) reduced significantly. The net result is that no detectable difference in gain is seen for these groups' first full motion run. All three groups were tracking with significantly lower gain than the MOTION group at Run 81 (Table 22). There does appear to be an advantage to training, per se, however. The Run 81 gain for the VELOCITY trained group was found to be significantly higher than that of the naïve MOTION group, despite the relatively high critical difference of about 5 db (Table 26). In fact, the STATIC, POSITION, and VELOCITY trained groups were operating with gain levels from about 3 to 5.5 db higher than the untrained (naïve) MOTION group.

Crossover frequency, ω_C, did not significantly change upon transition from the training to the full motion environment. However, there was no clear training benefit derived from the POSITION or VELOCITY training since no statistically significant differences among the STATIC, POSITION, or VELOCITY trained groups are observed at Run 81 (Table 20). It is not even clear that there was a training benefit along this dimension since naïve subjects did not perform detectably different from these three trained groups in their first full motion run (Table 24).

Similarly, no clear advantage of dynamic seat training was observed for "rolloff." While the steeper "rolloff" slopes achieved by the dynamic seat trained groups transitioned well, the STATIC trained group actually achieved a more MOTION-trained like "rolloff" at Run 81 than did the POSITION or VELOCITY groups (Table 23). It is even questionable whether there was an intrinsic advantage to training. Untrained MOTION subjects did not manifest a "rolloff" slope significantly different from that of the three trained groups (Table 27).

In sum, it was found that if there was a clear advantage gained by training, it was along the dimensions of gain and stability margin. Of these two, dynamic seat cuing during training seemed only to benefit development of proper (i.e., more similar to that adopted in a whole-body motion environment) stability margin performance—which was seen to transfer to the full motion environment.

4.3.5 Post-transition Control Behavior

In this section test results are presented for the crossover scores over four post-transition sessions. The intent of these tests was to determine where differences existed following transition to the criterion motion device, and when these differences disappeared. As with tracking error, a planned Split Plot Factorial (SPF) ANOVA was used to compare average scores for sessions 21, 24, 27, and 30. “Sessions” (Factor B) is the within block factor, and “Drive Law” (Factor A) and “Sex” (Factor C) are the two between block factors. The results are presented in Tables 28 through 31 for ω_C, φ_M, K_L, and “rolloff” respectively.

The ANOVA of ω_C (Table 28) shows a significant “Sessions” main effect (21% strength of association) and a significant “Drive Law” by “Sessions” interaction (7% strength of association). The “Significant AB” ANOVA detected a significant simple main effect of “Drive Law” at Session 21 (B1) and of “Sessions” at all levels of “Drive Law”, excepting MOTION ($p=.05/4=.0125$). That is to say, there was a difference among the groups at “Session” 21, but these differences were no longer detectable by “Session” 24. Further, all groups—other than MOTION—modified their crossover frequency after transitioning to the full motion environment.

The Tukey Pairwise Comparisons in Table 28 for “Drive Law” at “Session” 21 show only one pairwise difference, STATIC-MOTION, exceeding the 1.57 rad/s critical difference. The Pairwise Comparisons for “Sessions” at the STATIC, POSITION, and VELOCITY levels of “Drive Law” indicate a significant ω_C modification from “Session” 21 (B1) to “Session” 30 (B4). As stated earlier (Section 4.2.5), the other Factor B pairwise differences simply provide information regarding the shape of the post-transition learning curves.

The ANOVA of φ_M (Table 29) reveals a significant main effect of “Sessions” (13% strength of association) and a “Drive Law” by “Session” interaction (9% strength of association). The “Significant AB” ANOVA indicates a simple main effect of “Drive Law” at “Session” 21 (B1), and a simple main effect of “Sessions” for the STATIC group (A1). The Pairwise Comparisons for “Drive Law” at “Session” 21 show only the STATIC-MOTION difference exceeding the 10 degree critical difference, and this difference is no longer significant by “Session” 24. The Pairwise Comparisons for “Sessions” at the STATIC level of “Drive Law” is indicative of a significant exponential-like change in φ_M (also apparent in Fig. 29). No significant post-transition change in φ_M is observed for either of the dynamic seat trained groups. This is consistent with the findings of the “transition” tests (Table 21) which showed that all groups maintained their φ_M level upon transitioning to the whole-body motion environment. Only the STATIC group was performing markedly different from the MOTION group at transition, and so had to learn to modify its φ_M following transition.

The ANOVA of K_L (Table 30) shows a significant main effect of “Drive Law” (15% strength of association) and “Sessions” (26% strength of association), plus a significant “Drive Law” by “Session” interaction (12% strength of association). There is a simple main effect of “Drive Law” only at “Session” 21, and a simple main effect of “Sessions” at the STATIC, POSITION, and VELOCITY levels of “Drive Law.” The STATIC, POSITION, and VELOCITY group gains are all significantly different from that of the MOTION group at “Session” 21, a result equivalent to that obtained by the “transition” test at Run 81 (Table 22). This difference is no longer detectable (with a critical difference of 3.7 db) at “Session” 24. The simple main effect of “Sessions” at the three levels of “Drive Law” again indicates that these three groups significantly modified their behavior following transition to the whole-body motion environment.

The ANOVA of open-loop gain “rolloff” (Table 31) shows a main effect of “Sessions” (16% strength of association), indicating only that average post-transition “rolloff” was modified. Differences due to “Drive Law,” when averaged over sessions, are not large enough for its main effect or any interaction to be significant. This is not surprising in light of the small differences found in the “transition” Tukey Tests conducted on “rolloff” at Run 81 (Table 23).

Tables 32 through 35 (for ω_C, φ_M, K_L, and “rolloff” respectively) contain the results of an unplanned ANOVA set comparing post-transition control behavior for the STATIC, POSITION, and VELOCITY trained groups to that of a group of untrained MOTION subjects. A significant effect of “Sessions” is observed for each group in each crossover score ANOVA. This indicates that all groups were modifying their control behavior along all four crossover dimensions. A difference due to training condition ("Drive Law") is seen only for K_L (Table 34). Here it is observed that both the POSITION and VELOCITY trained groups were operating at a significantly higher gain level than was the MOTION group in that first full motion session. These differences were no longer detectable, however, by the fourth full motion session.

In sum, the comparisons of the crossover scores across the range of post-transition sessions bear out the findings of the "transition" tests (Section 4.3.4). That is, only two of the crossover variables considered showed any significant benefit from training. These were phase margin and gain. It was also observed that where a significant training condition effect was detected for the first full motion session, this was no longer detectable by the fourth full motion session.

4.3.6 Discussion of the Results of Comparisons of Transition and Post-transition Control Behavior

The data show that training with dynamic seat cues helped subjects adopt a phase (or stability) margin much like that adopted in the full motion environment. Further, this was seen to transition smoothly from the training condition to the full motion environment (Table 21; Fig. 29 through 32). It was also observed that only the STATIC group significantly modified its stability margin following "transition" (Table 29). Detectable differences resulting from the STATIC training condition disappeared by "Session" 24 (Runs 93-96). In the φ_M comparisons of the trained STATIC, POSITION, and VELOCITY groups to naïve subjects starting out in a full motion environment (Table 33), no significant training condition effect was detected. However, during the first full motion session the POSITION and VELOCITY groups were operating at phase margin levels which were about 11-12 degrees lower than that of the naïve MOTION group; the STATIC group was operating about 3 degrees lower than the MOTION group.

No significant differences in gain, K_L, were observed among the STATIC, POSITION, or VELOCITY groups for the first post-transition run (Run 81 in Table 22) or "Session" (Session 21 in Table 30). (Gain is plotted versus tracking runs in Fig. 33 through 36.) All three groups were seen to have significantly modified their gain over the post-transition sessions (Table 30), which is an indication that these groups were still learning to use available motion information in the full motion environment. Yet, the comparisons of trained STATIC, POSITION, and

VELOCITY groups' gain to that of the naïve MOTION group revealed significantly higher K_L for the VELOCITY group on the first full motion run (Table 26), and (because the experimental error was lower) for both the POSITION and VELOCITY groups on the first full motion session (Table 34). This effect was no longer significant by the fourth full motion session.

Crossover frequency (ω_C), shown in Fig. 25 through 28, is considered next. Although ω_C transferred relatively smoothly (the VELOCITY group is a possible exception—though not significant statistically—its ω_C dropped more than 1 rad/s), both the STATIC and VELOCITY groups had significantly lower ω_C than the MOTION group at Run 81 (Table 20). The average "Session" 21 score (Table 28) shows that the STATIC ω_C was significantly lower than that for MOTION (but not significantly different from that of POSITION or VELOCITY, which were both about 1.5 rad/s lower than MOTION's); in any case, all significant differences disappeared by "Session" 24 (Runs 93-96). In the comparison of trained STATIC, POSITION, and VELOCITY groups to the untrained MOTION group, no significant training condition effect was observed in the first full motion session (Table 32); in fact, all group session means were within 1 rad/s of each other.

The dynamic seat groups were seen to have adopted a "rolloff" slope very similar to that of the MOTION trained group late in training (Fig. 37 through 40). Upon transition (Run 81), however, the STATIC group adopted a "rolloff" slope closer (although not significantly closer) to that of the MOTION group than either the POSITION or VELOCITY group (Table 23). Differences among the "rolloff" levels adopted by the STATIC, POSITION, and VELOCITY groups over the first post-transition session were less than 1 db/decade (Table 31). When the "rolloff" scores for the first full motion session are compared among the STATIC, POSITION, and VELOCITY trained groups and the untrained MOTION group (Table 35), no significant effect of training condition is found (first session group scores are within 3 db/decade of each other).

In sum, there appears to be <u>some benefit</u> observable in dynamic seat training, <u>but it is not strong</u>. On the other hand, training in a STATIC environment was not significantly better than no training at all for this experimental task (i.e., no effect of STATIC training was detected in the comparisons against untrained MOTION subjects). Dynamic seat training did help subjects adopt a proper stability margin, and the subjects were able to carry this over to the whole-body motion environment. There was also some training condition effect on gain. Subjects trained with seat cues operated with significantly higher gains upon initial exposure to the full motion environment than did subjects with no previous training.

4.4 Conclusions

The experimental results clearly demonstrate that motion information can be effectively imparted tactually via a seat pan. Subjects used this information to develop a level of performance and control behavior equivalent to that adopted by trackers in a whole-body motion environment, as measured along several dimensions. Near asymptotic tracking error, open-loop man-vehicle crossover frequency, low-frequency gain, gain "rolloff" in the vicinity of crossover, and phase margin were not detectably different between a group of VELOCITY "Drive Law" dynamic seat trackers and a group of whole-body motion trackers. A POSITION "Drive Law" was also evaluated, but did not turn out to be as effective as the VELOCITY "Drive Law" in eliciting motion-equivalent performance and control behavior. The POSITION "Drive Law" still proved more effective than visual cues alone (STATIC tracking).

No significant training condition effect was detected for learning rate, where the training conditions included whole-body motion, dynamic seat cuing with both the VELOCITY and POSITION "Drive Laws," and STATIC tracking. The learning rates tested were the least square estimates obtained by fitting an asymptotic, exponential-decay model to the tracking error data.

Although whole-body motion equivalent performance and control behavior were elicited during training for dynamic seat subjects, this equivalence did not transfer to the actual motion environment well. Subjects trained with seat cues did develop a proper phase margin characteristic, and did transfer this to the motion environment. Seat trained subjects were also observed to track with significantly higher gain than untrained subjects, upon first exposure to the actual motion environment. That was the extent to which dynamic seat cue training was observed to help subjects (with no previous tracking experience in a whole-body motion environment) pick up and use the motion information available to them in a whole-body motion environment.

It appears that the dynamic seat may well be a useful device in engineering simulators where the interest is in establishing whole-body motion equivalence. However, the dynamic seat—with the "Drive Laws" used in this experiment—does not appear to be useful for training subjects inexperienced in the full motion environment to effectively use the motion information available in that environment.

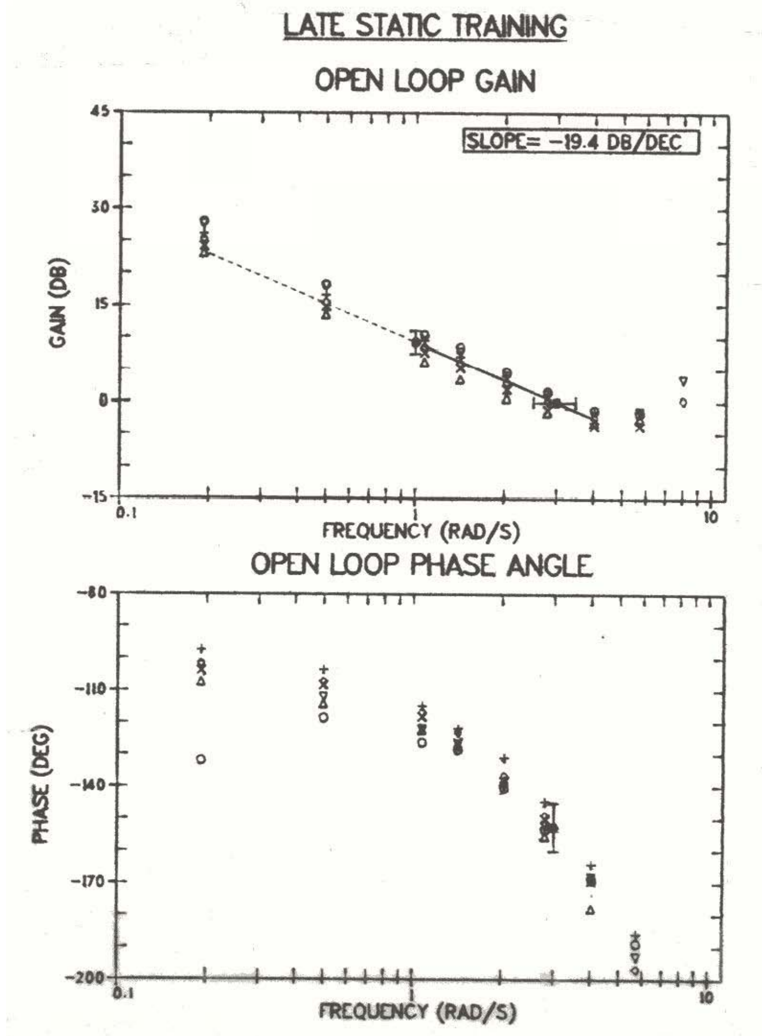

Figure 9. "Late training" open loop gain and phase estimates for the STATIC group

The solid circles with standard deviation bars are the means, averaged across the six group members for runs 65-80, of the estimates for gain, crossover frequency, and the phase angle corresponding to the phase margin. The line faired through the gain data has a slope corresponding to the mean value of the "rolloff." The solid portion of the line indicates the range of the data included in the individual least squares fits used to obtain the estimates for gain and rolloff. The dashed extension of the line below 1 rad/s is provided for reference. The remaining symbols each correspond to the sixteen-run average of valid gain and phase estimates for a subject at the corresponding frequency. The open circle, "+," and diamond symbols identify data corresponding to the three male subjects (subjects 3, 10, and 19 respectively). The point-up triangle, "X," and point-down triangle symbols identify those data for the three female subjects (subjects 8, 15, and 23 respectively).

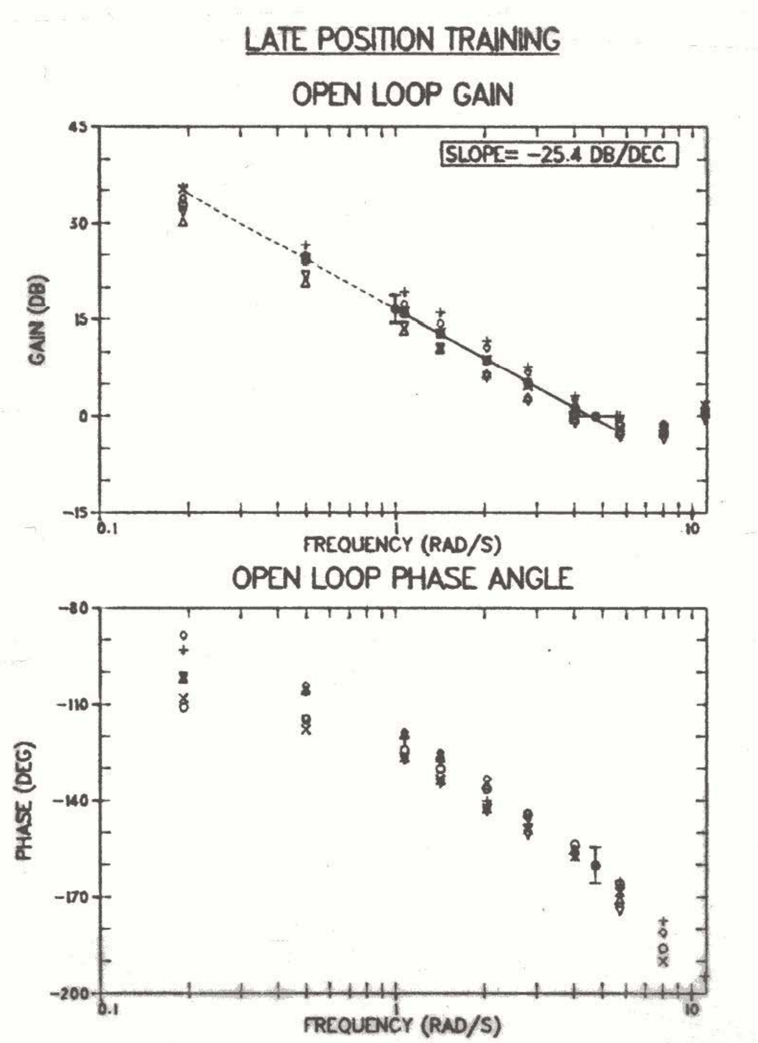

Figure 10. "Late training" open loop gain and phase estimates for the <u>POSITION group</u>
The solid circles with standard deviation bars are the means, averaged across the six group members for runs 65-80, of the estimates for gain, crossover frequency, and the phase angle corresponding to the phase margin. The line faired through the gain data has a slope corresponding to the mean value of the "rolloff." The solid portion of the line indicates the range of the data included in the individual least squares fits used to obtain the estimates for gain and rolloff. The dashed extension of the line below 1 rad/s is provided for reference. The remaining symbols each correspond to the sixteen run average of valid gain and phase estimates for a subject at the corresponding frequency. The open circle, "+," and diamond symbols identify data corresponding to the three male subjects (subjects 2, 11, and 18 respectively). The point-up triangle, "X," and point-down triangle symbols identify those data for the three female subjects (subjects 5, 14, and 22 respectively).

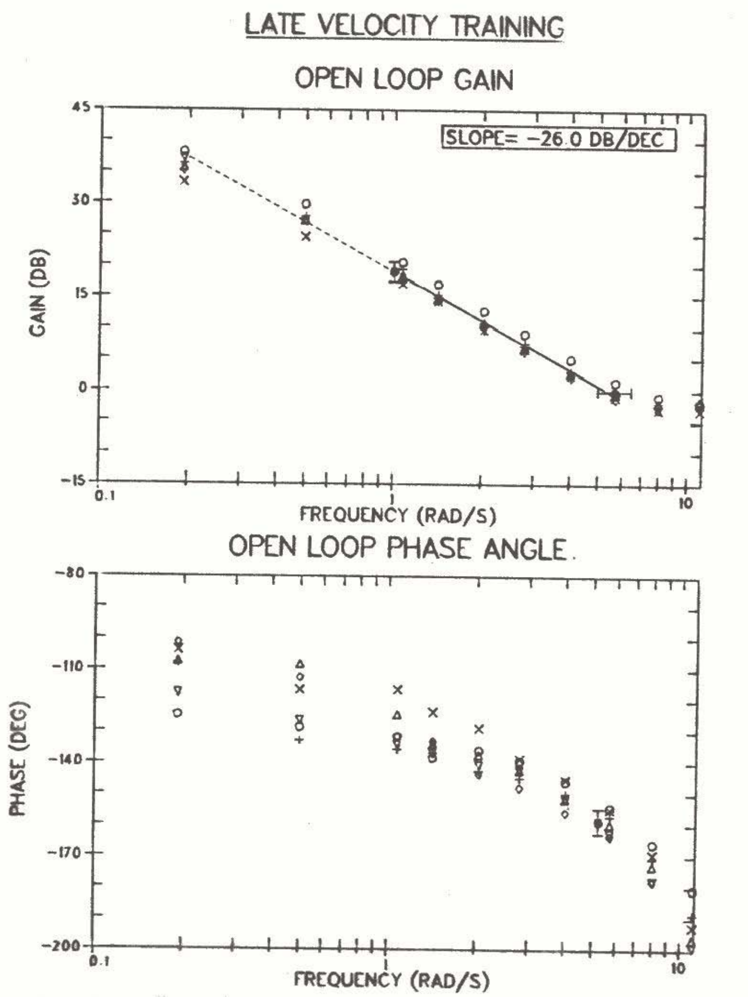

Figure 11. "Late training" open loop gain and phase estimates for the VELOCITY group The solid circles with standard deviation bars are the means, averaged across the six group members for runs 65-80, of the estimates for gain, crossover frequency, and the phase angle corresponding to the phase margin (the phase angle mean has been shifted leftward slightly for clarity). The line faired through the gain data has a slope corresponding to the mean value of the "rolloff." The solid portion of the line indicates the range of the data included in the individual least squares fits used to obtain the estimates for gain and "rolloff." The dashed extension of the line below 1 rad/s is provided for reference. The remaining symbols each correspond to the sixteen run average of valid gain and phase estimates for a subject at the corresponding frequency. The open circle, "+," and diamond symbols identify data corresponding to the three male subjects (subjects 1, 12, and 20 respectively). The point-up triangle, "X," and point-down triangle symbols identify those data for the three female subjects (subjects 7, 13, and 21 respectively).

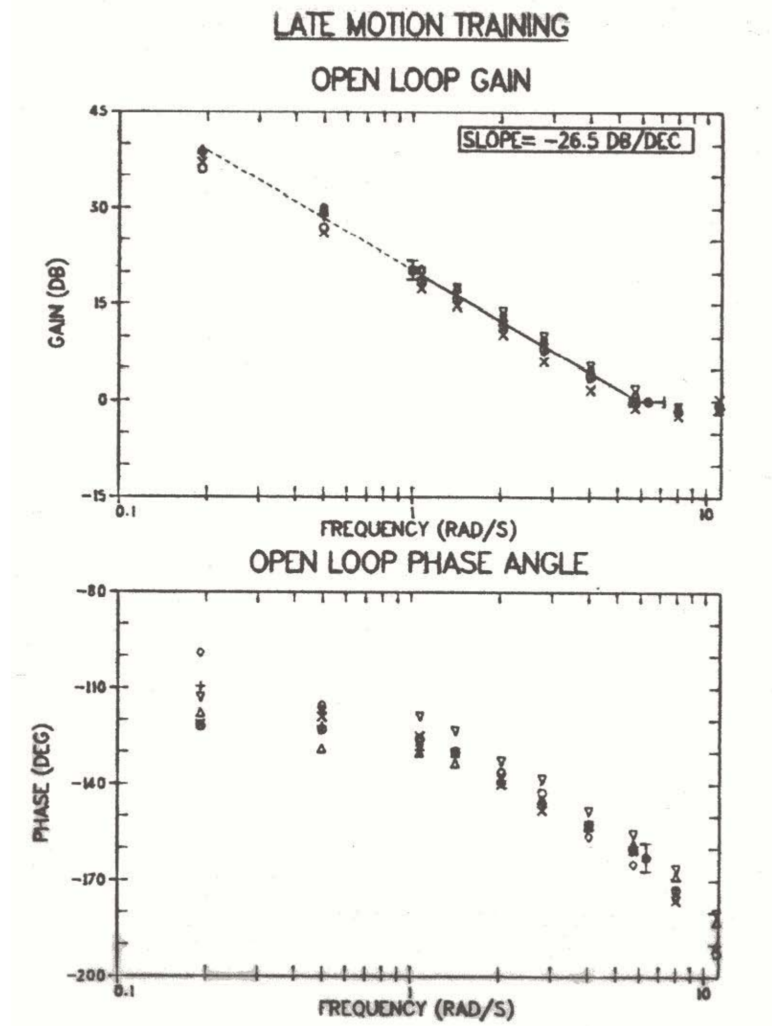

Figure 12. "Late training" open loop gain and phase estimates for the <u>MOTION group</u>
The solid circles with standard deviation bars are the means, averaged across the six group members for runs 65-80, of the estimates for gain, crossover frequency, and the phase angle corresponding to the phase margin. The line faired through the gain data has a slope corresponding to the mean value of the "rolloff." The solid portion of the line indicates the range of the data included in the individual least squares fits used to obtain the estimates for gain and rolloff. The dashed extension of the line below 1 rad/s is provided for reference. The remaining symbols each correspond to the sixteen run average of valid gain and phase estimates for a subject at the corresponding frequency. The open circle, "+," and diamond symbols identify data corresponding to the three male subjects (subjects 4, 9, and 17 respectively). The point-up triangle, "X," and point-down triangle symbols identify those data for the three female subjects (subjects 6, 16, and 24 respectively).

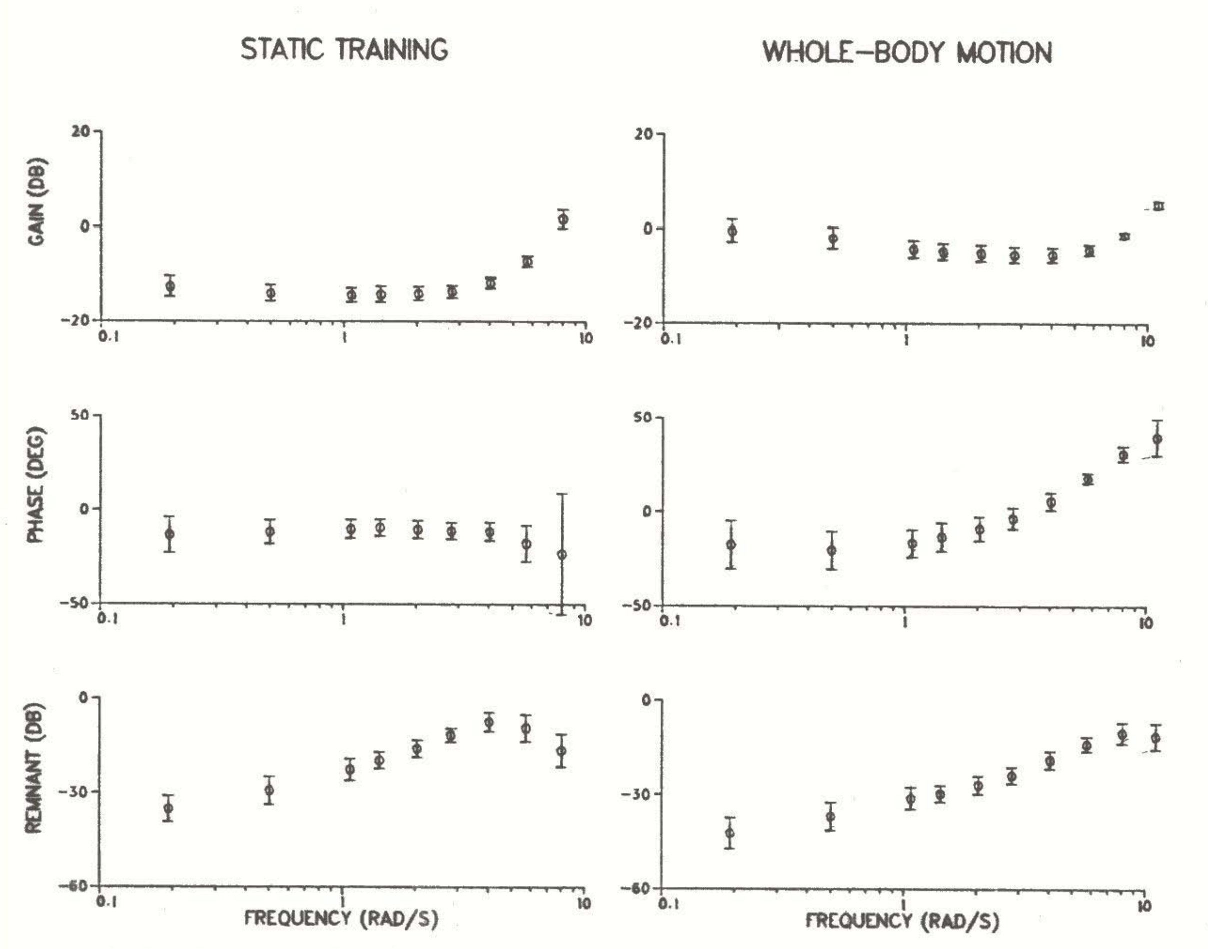

Figure 13. Human Operator Describing Function (HODF) for the <u>STATIC group</u> with measured remnant

These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

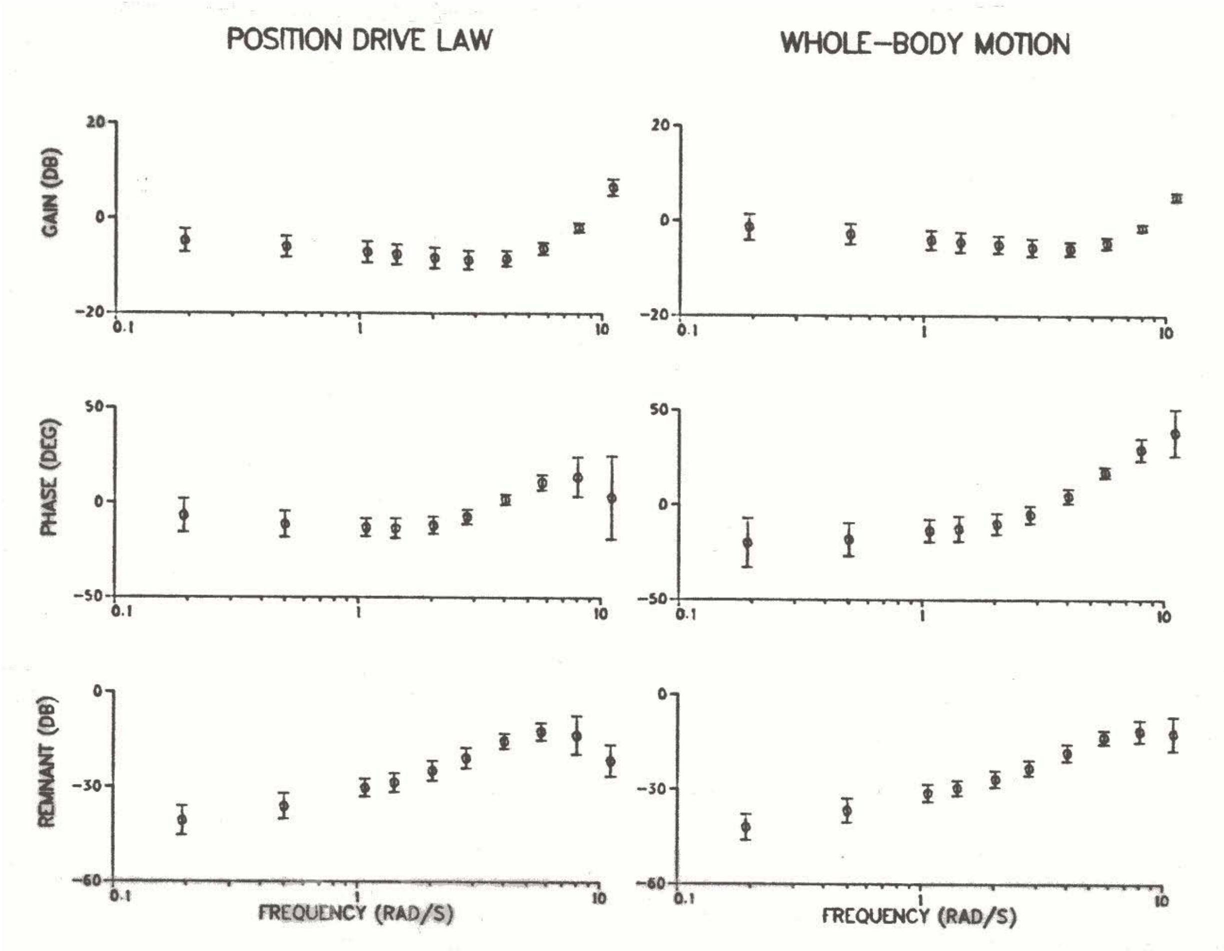

Figure 14. HODF for the <u>POSITION group</u> with measured remnant

These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

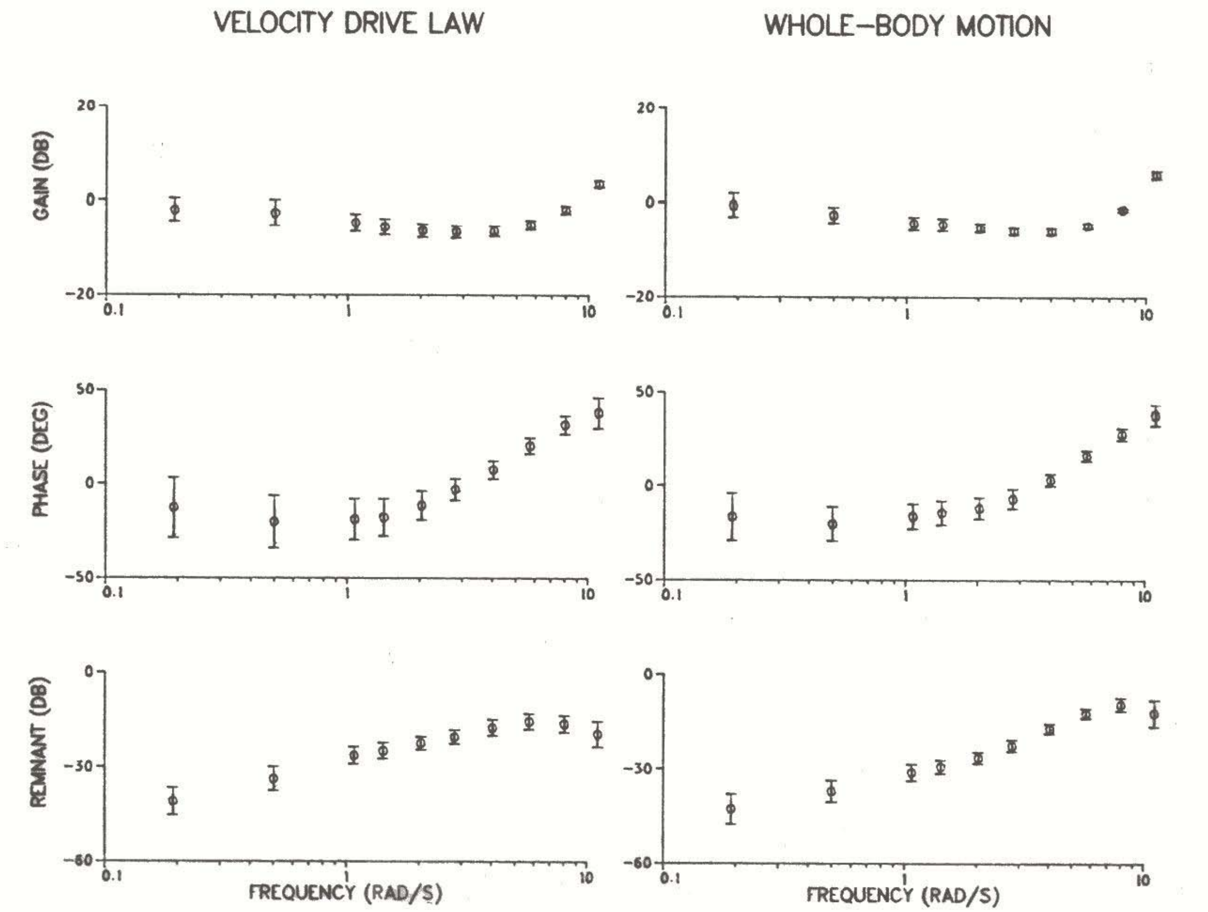

Figure 15. HODF for the __VELOCITY group__ with measured remnant

These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

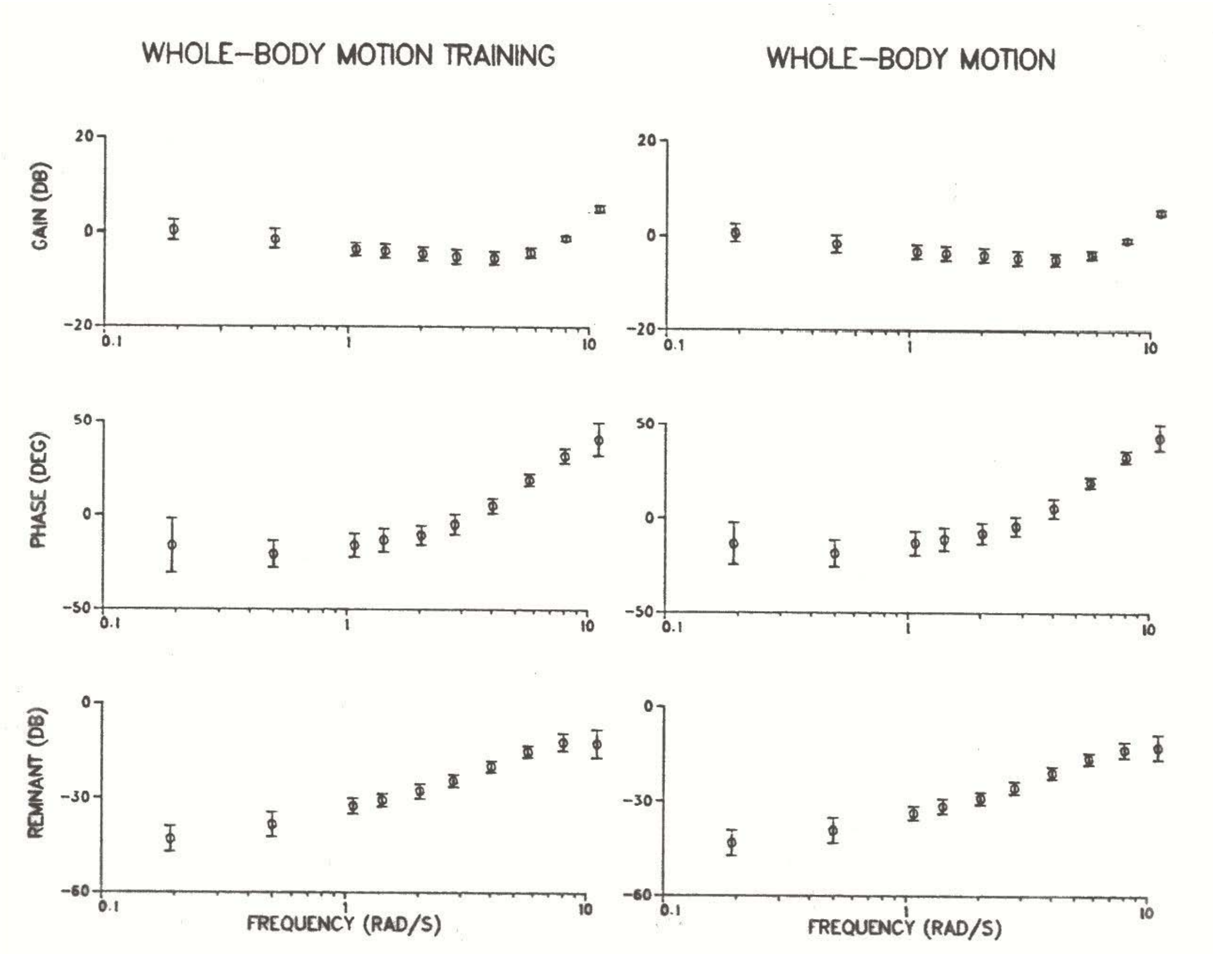

Figure 16. HODF for the <u>MOTION group</u> with measured remnant

These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

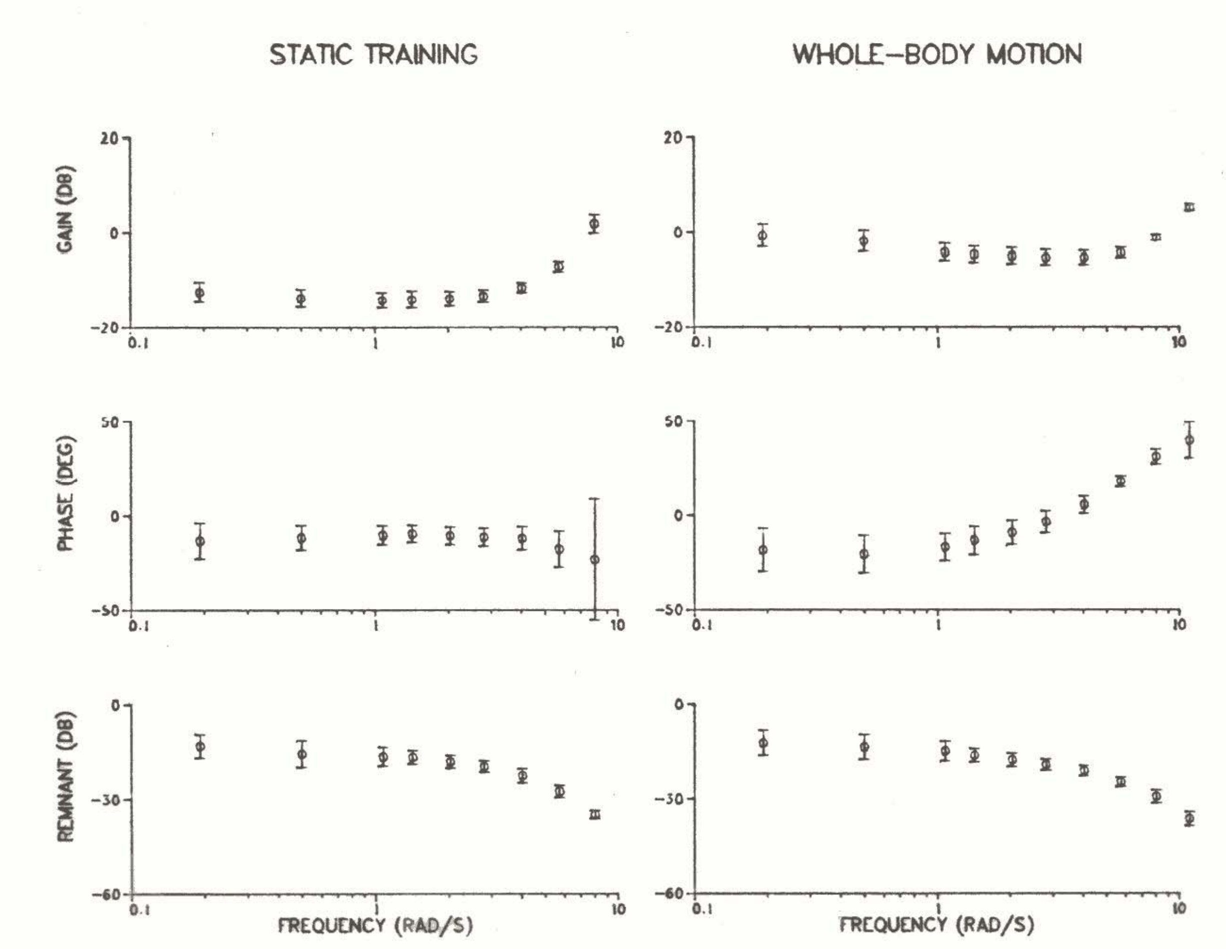

Figure 17. HODF for the STATIC group with remnant referred to the operator's input
These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the open-loop REMNANT, normalized by the error variance and referred to the operator's input, accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and 1 $(rad/s)^{-1}$ for REMNANT.

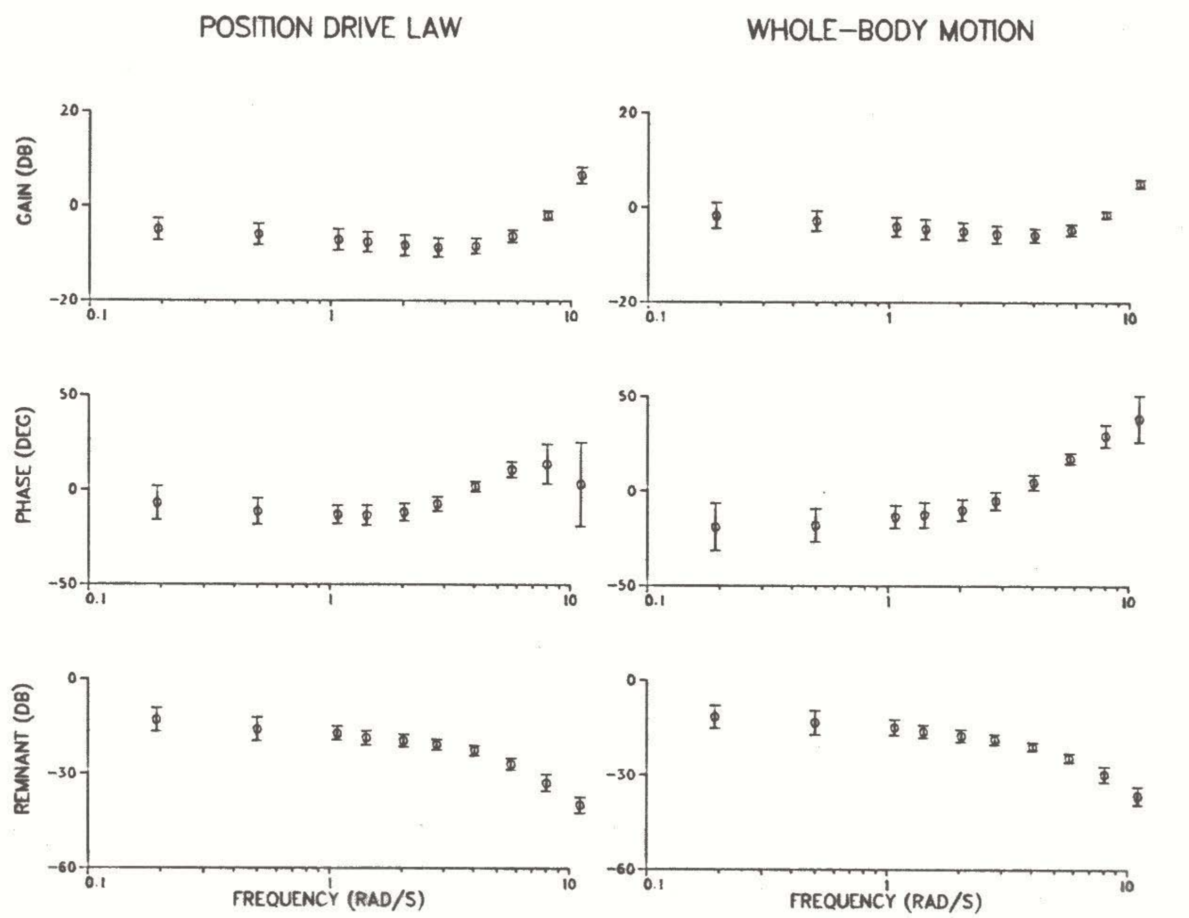

Figure 18. HODF for the POSITION group with remnant referred to the operator's input
These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the open-loop REMNANT, normalized by the error variance and referred to the operator's input, accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and 1 $(rad/s)^{-1}$ for REMNANT.

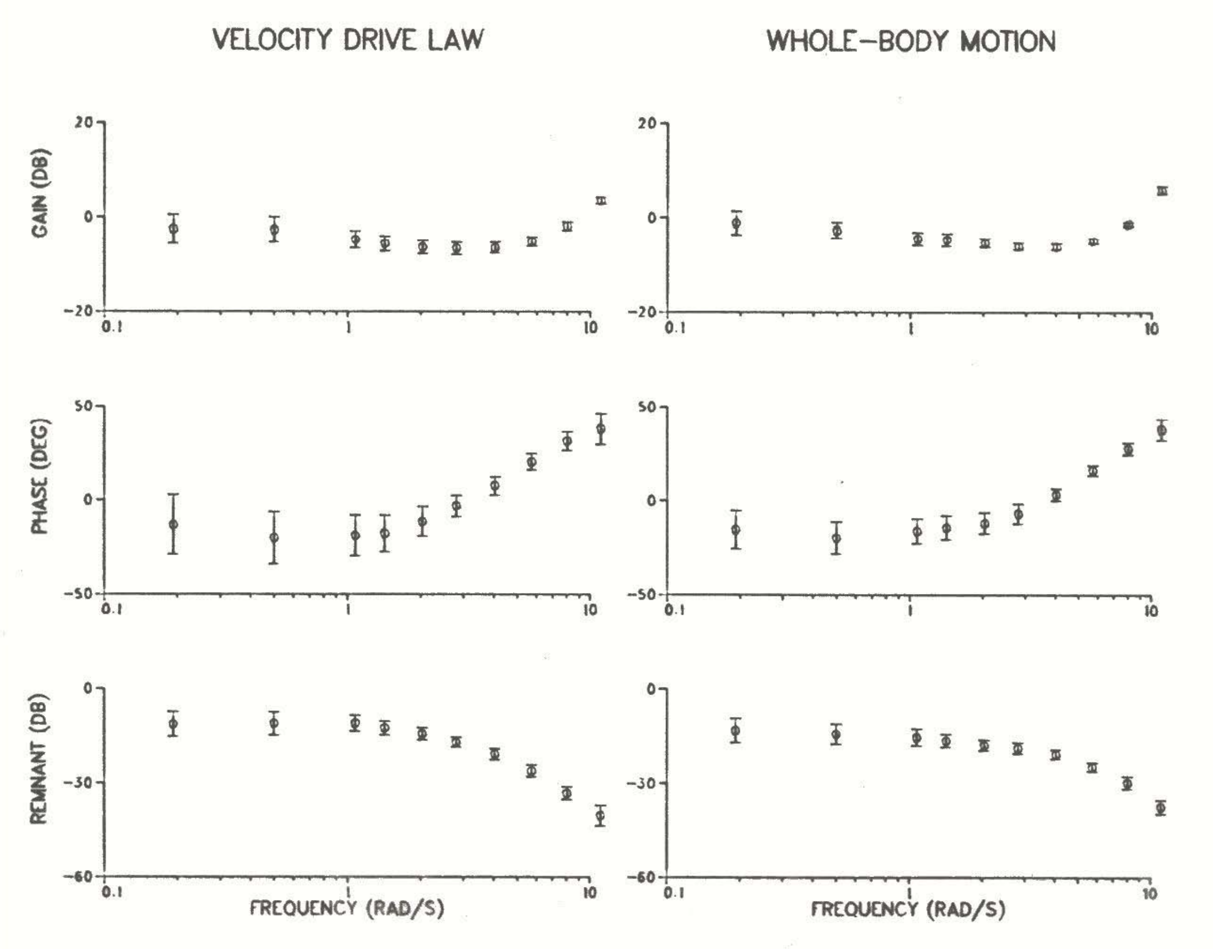

Figure 19. HODF for the VELOCITY group with remnant referred to the operator's input These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the open-loop REMNANT, normalized by the error variance and referred to the operator's input, accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and 1 $(rad/s)^{-1}$ for REMNANT.

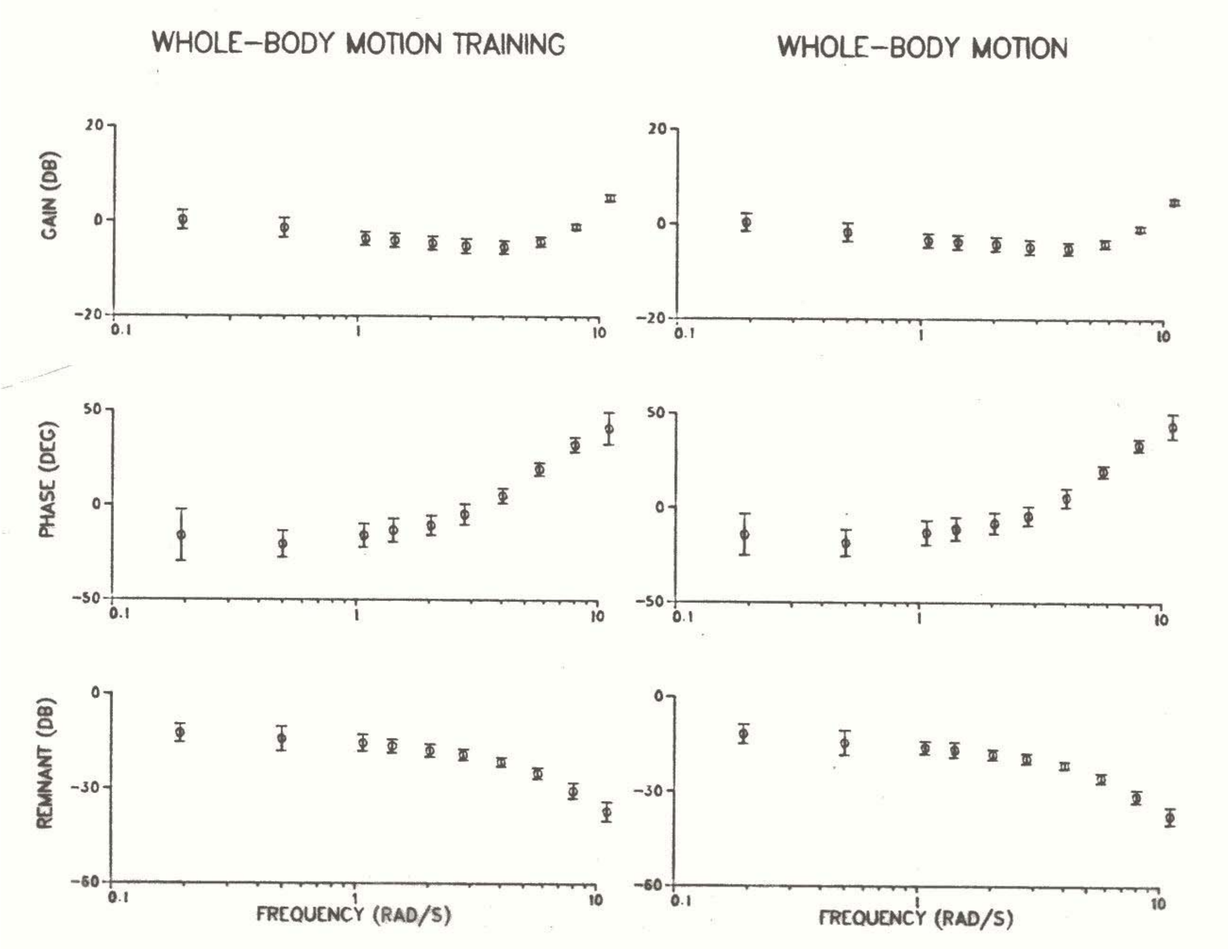

Figure 20. HODF for the MOTION group with remnant referred to the operator's input

These data are averaged across the six group members and sixteen runs. The left figure reflects average control behavior late in the training environment (runs 65-80). The right figure shows data for late post-transition to the whole-body motion environment (runs 105-120). Mean values, plus and minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the open-loop REMNANT, normalized by the error variance and referred to the operator's input, accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and 1 $(rad/s)^{-1}$ for REMNANT.

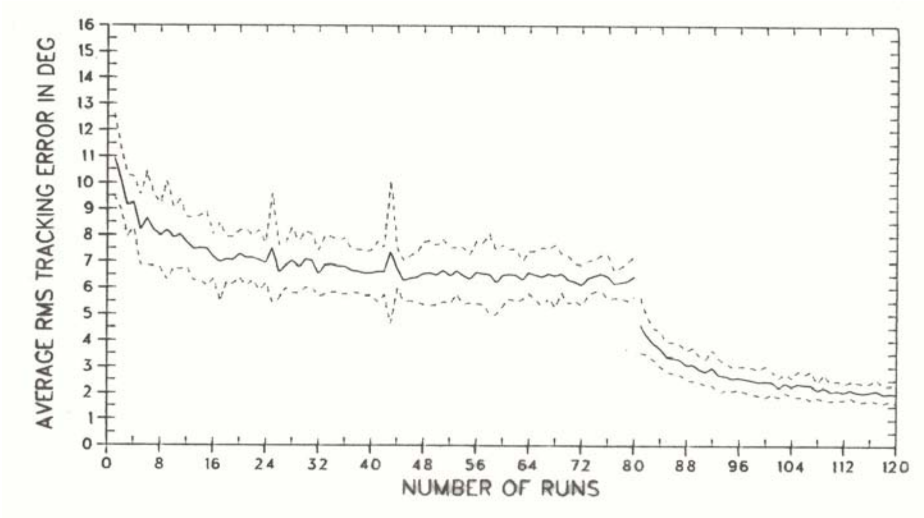

Figure 21. Tracking performance for the STATIC group

The solid line portrays the tracking error score, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided only visual cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

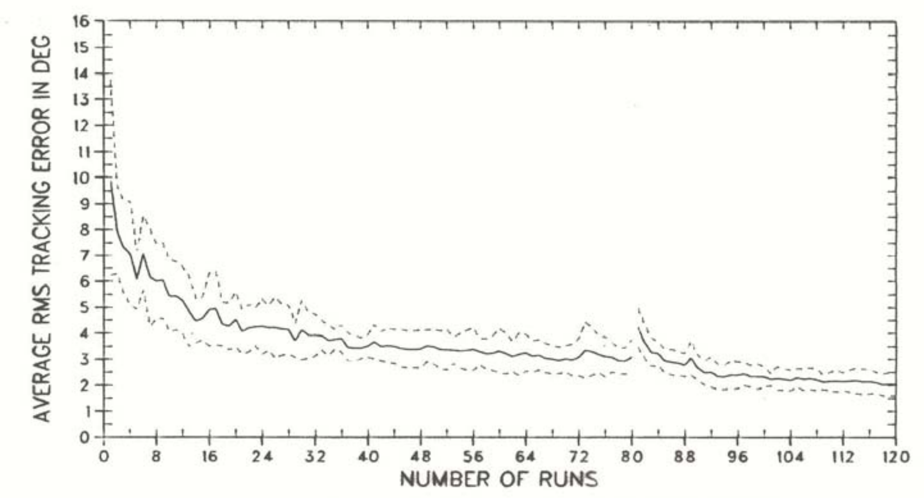

Figure 22. Tracking performance for the POSITION group

The solid line portrays the tracking error score, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "POSITION Drive law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

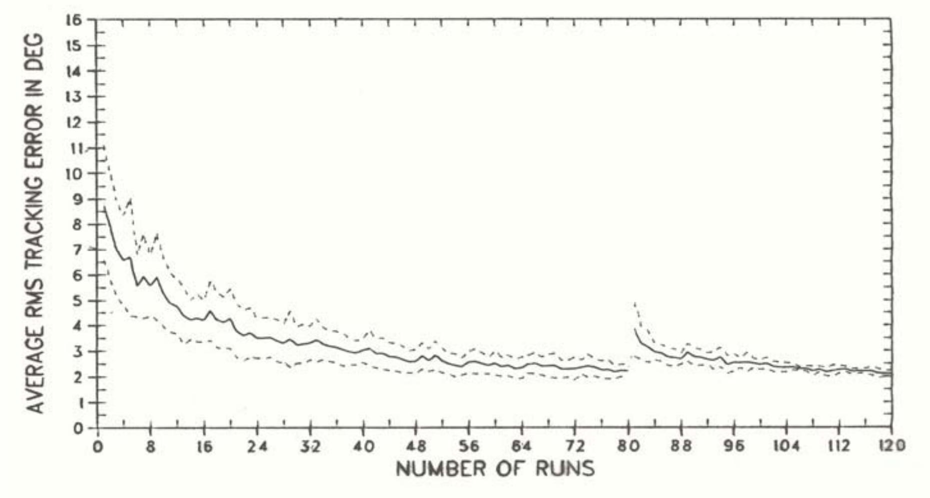

Figure 23. Tracking performance for the <u>VELOCITY group</u>

The solid line portrays the tracking error score, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "VELOCITY Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

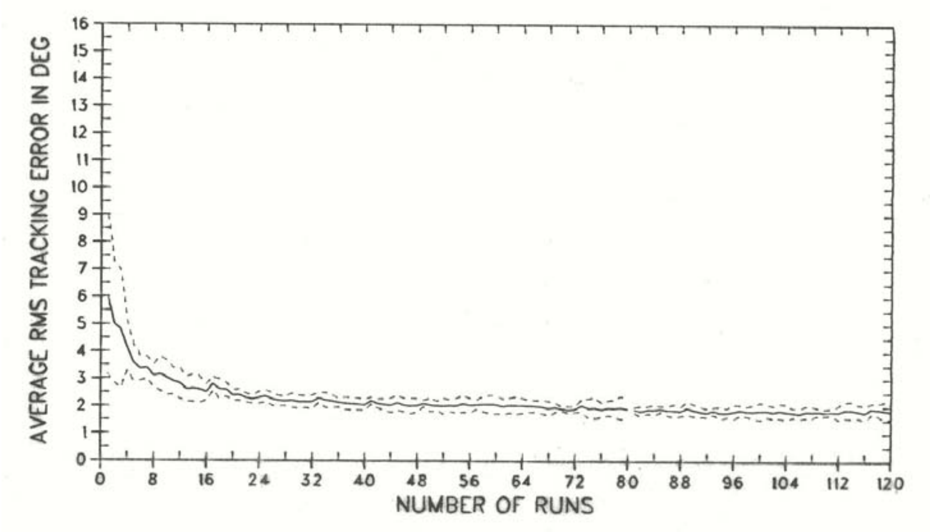

Figure 24. Tracking performance for the <u>MOTION group</u>

The solid line portrays the tracking error score, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided one-to-one whole-body motion cues during runs 1 through 120. The discontinuity in the solid line between runs 80 and 81 corresponds to the point at which the other three groups were transitioned to the whole-body motion environment.

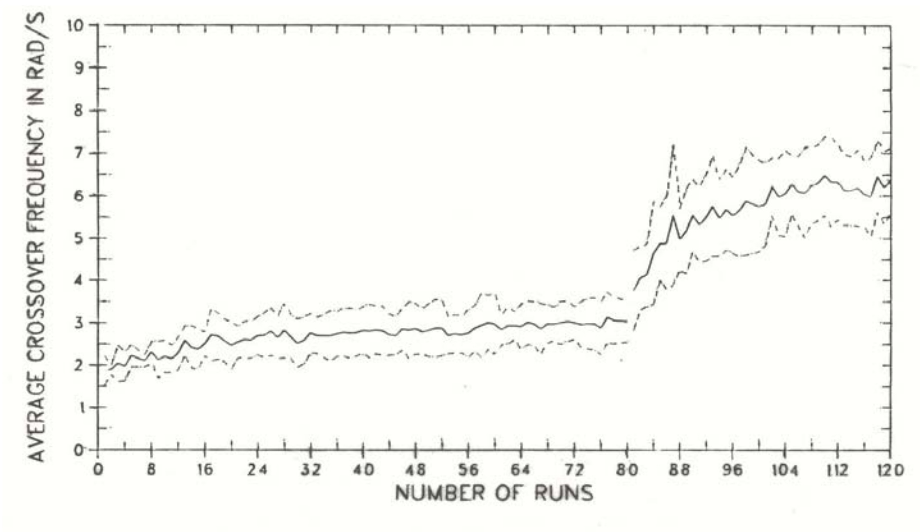

Figure 25. Crossover frequency for the STATIC group

The solid line portrays the crossover frequency estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided only visual cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

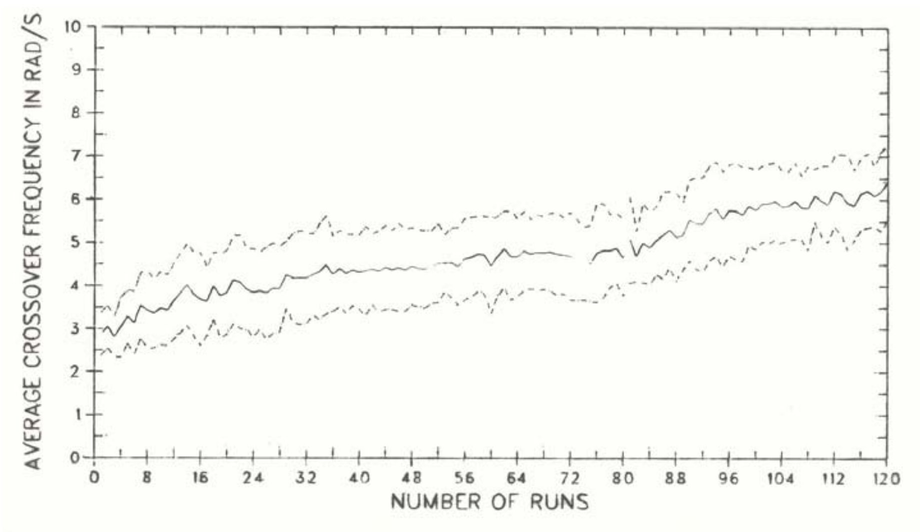

Figure 26. Crossover frequency for the POSITION group

The solid line portrays the crossover frequency estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "POSITION Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

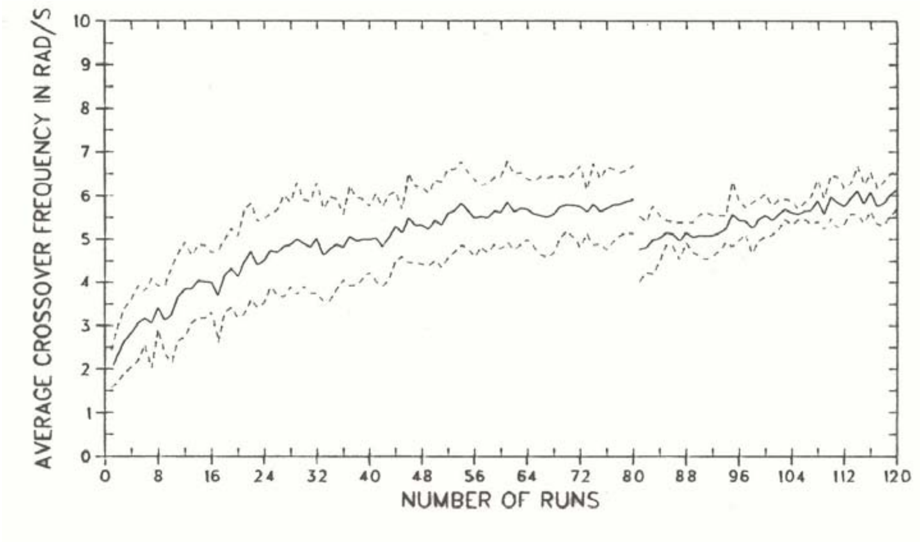

Figure 27. Crossover frequency for the <u>VELOCITY group</u>

The solid line portrays the crossover frequency estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "VELOCITY Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

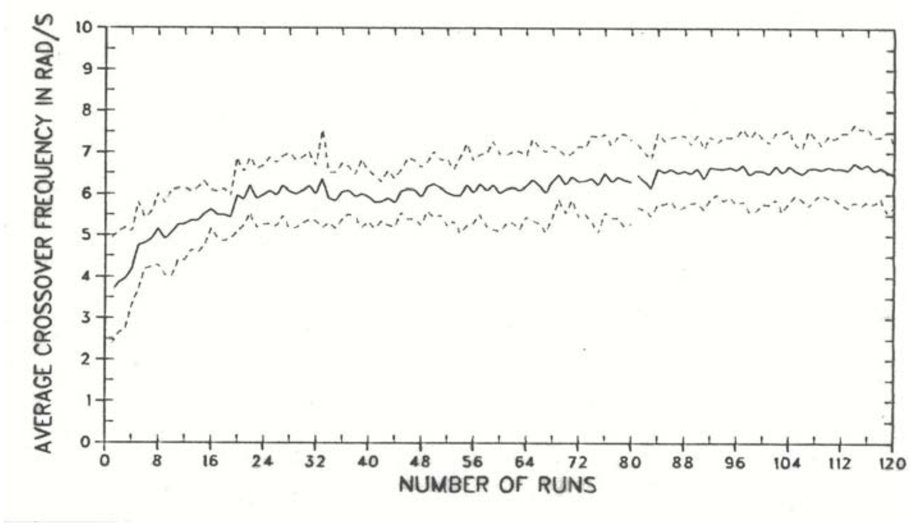

Figure 28. Crossover frequency for the <u>MOTION group</u>

The solid line portrays the crossover frequency estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided one-to-one whole-body motion cues during runs 1 through 120. The discontinuity in the solid line between runs 80 and 81 corresponds to the point at which the other three groups were transitioned to the whole-body motion environment.

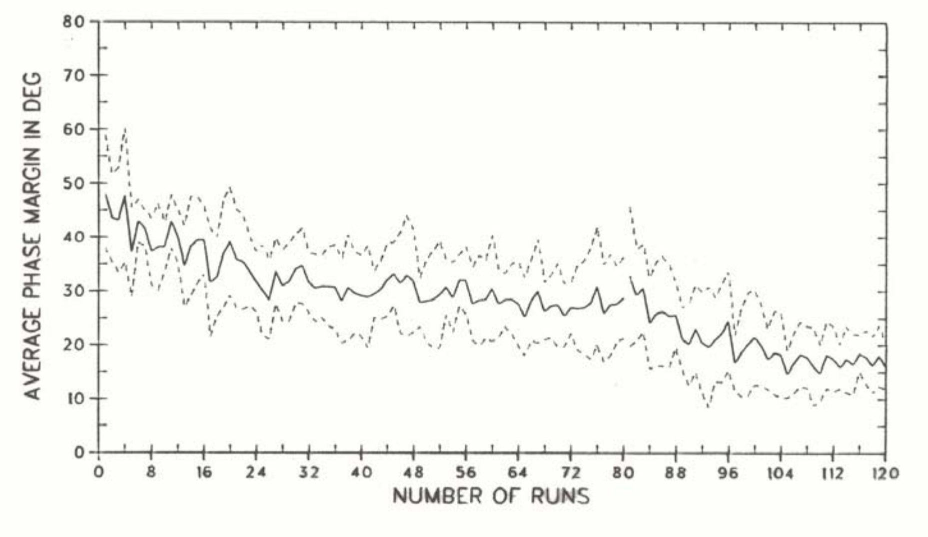

Figure 29. Phase margin for the <u>STATIC group</u>

The solid line portrays the phase (stability) margin estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided only visual cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

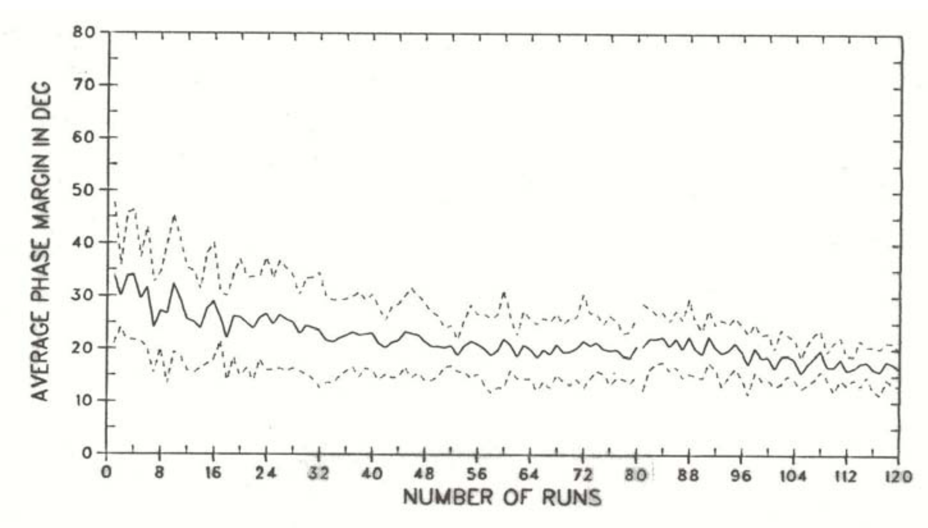

Figure 30. Phase margin for the <u>POSITION group</u>

The solid line portrays the phase (stability) margin estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "POSITION Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

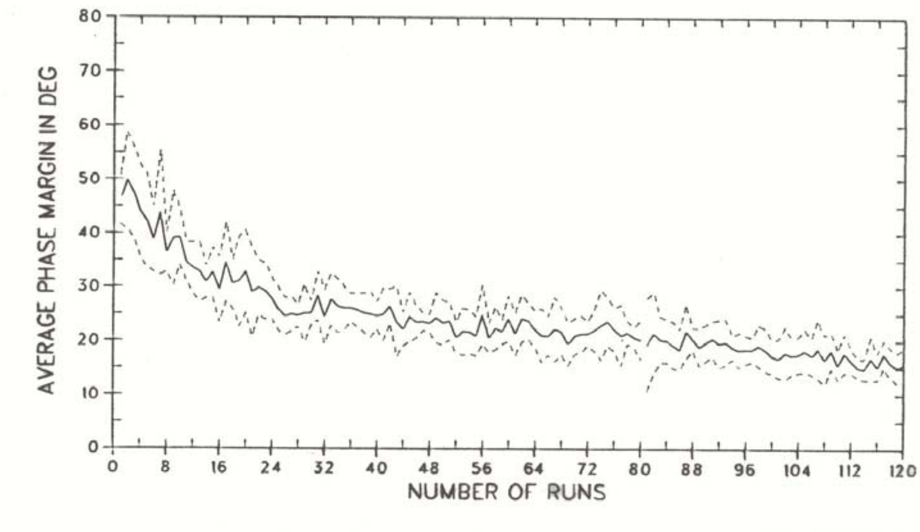

Figure 31. Phase margin for the <u>VELOCITY group</u>

The solid line portrays the phase (stability) margin estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "VELOCITY Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

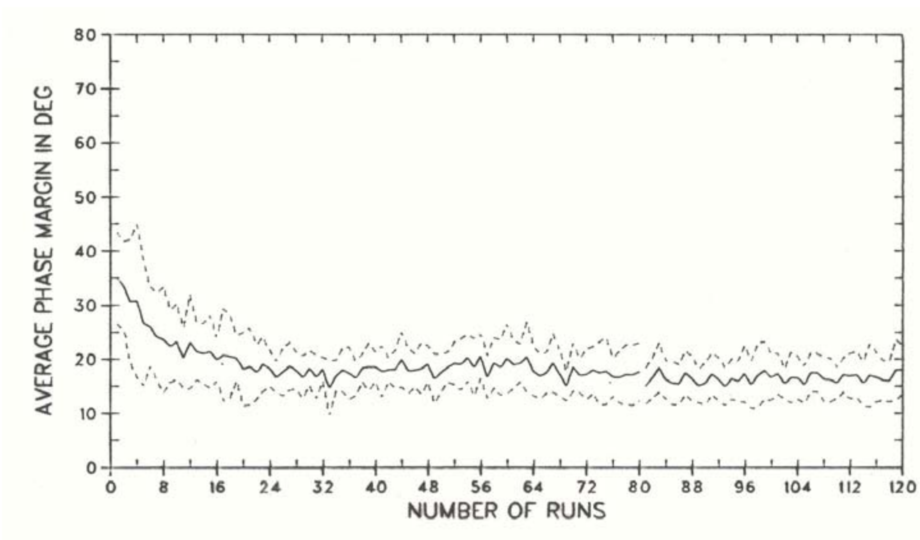

Figure 32. Phase margin for the <u>MOTION group</u>

The solid line portrays the phase (stability) margin estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided one-to-one whole-body motion cues during runs 1 through 120. The discontinuity in the solid line between runs 80 and 81 corresponds to the point at which the other three groups were transitioned to the whole-body motion environment.

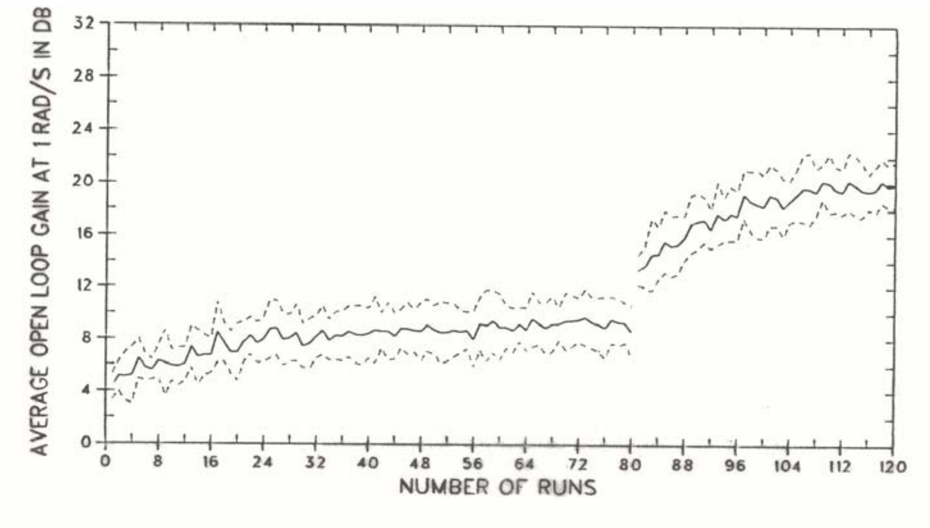

Figure 33. Open loop gain for the STATIC group

The solid line portrays the low-frequency open loop gain estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided only visual cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

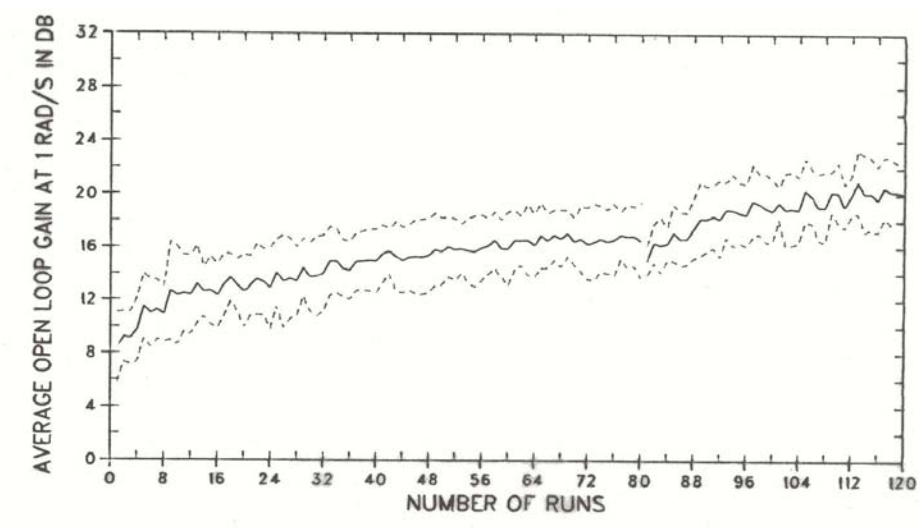

Figure 34. Open loop gain for the POSITION group

The solid line portrays the low-frequency open loop gain estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "POSITION Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

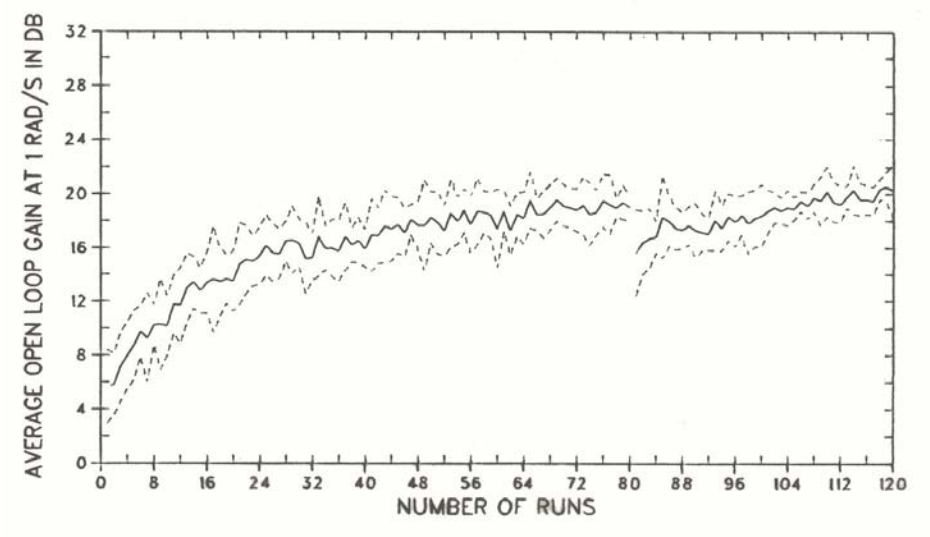

Figure 35. Open loop gain for the VELOCITY group

The solid line portrays the low-frequency open loop gain estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "VELOCITY Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

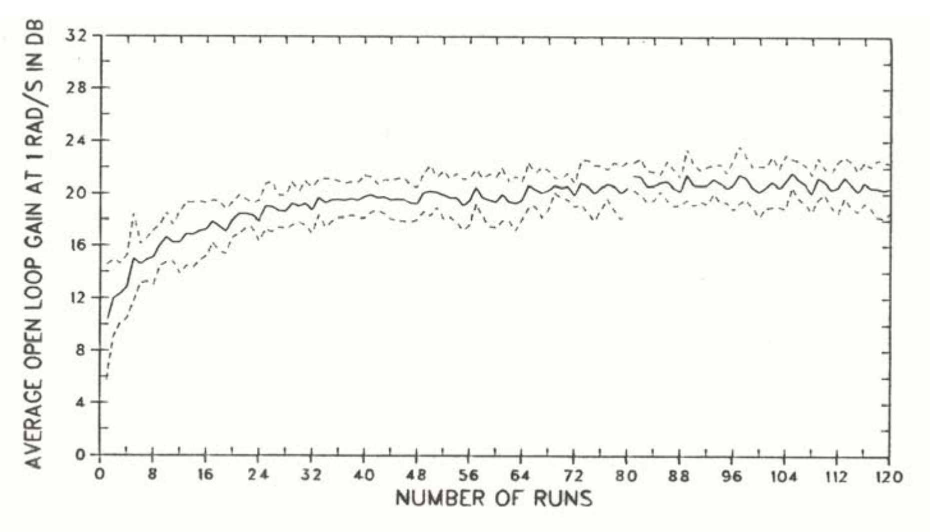

Figure 36. Open loop gain for the MOTION group

The solid line portrays the low-frequency open loop gain estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided one-to-one whole-body motion cues during runs 1 through 120. The discontinuity in the solid line between runs 80 and 81 corresponds to the point at which the other three groups were transitioned to the whole-body motion environment.

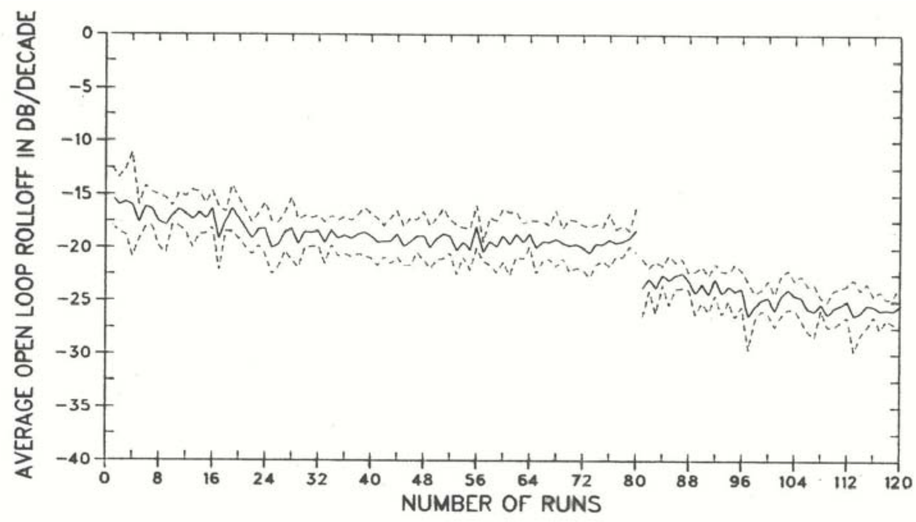

Figure 37. Open loop gain rolloff for the STATIC group

The solid line portrays the gain "rolloff" slope estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided only visual cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

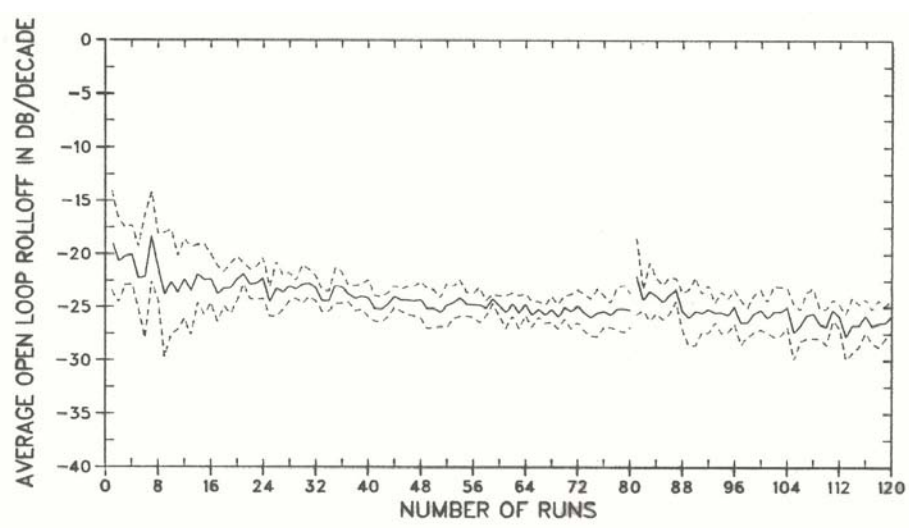

Figure 38. Open loop gain rolloff for the POSITION group

The solid line portrays the gain rolloff slope estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "POSITION Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

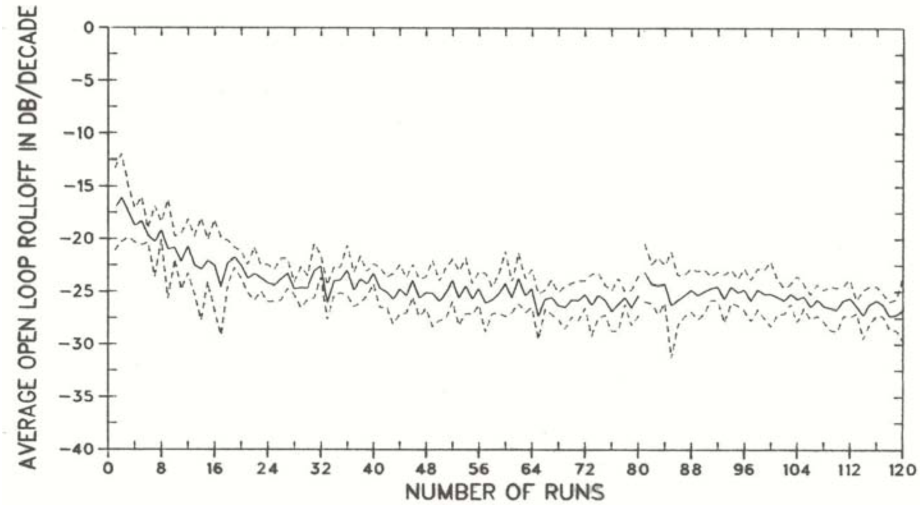

Figure 39. Open loop gain rolloff for the <u>VELOCITY group</u>

The solid line portrays the gain rolloff slope estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided "VELOCITY Drive Law" seat cues during runs 1 through 80. At run 81 the subjects were transitioned to a one-to-one whole-body motion environment. They continued to track in the whole-body motion environment through run 120.

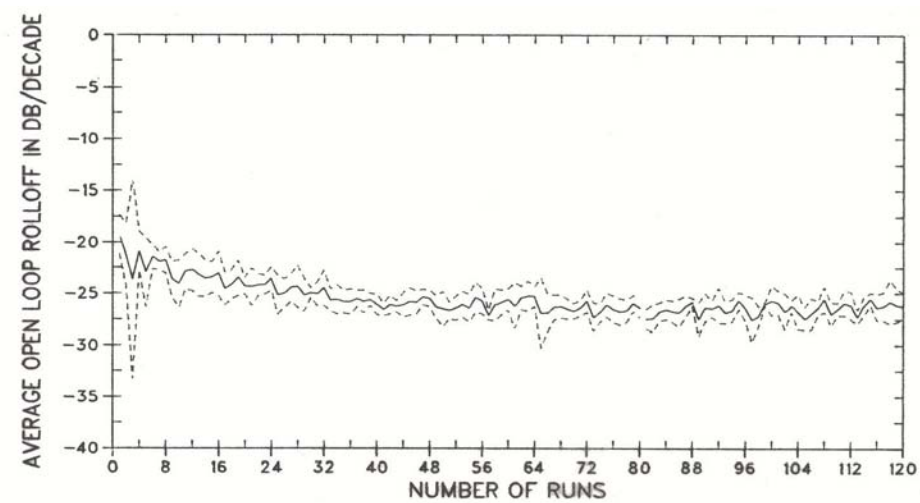

Figure 40. Open loop gain "rolloff" for the <u>MOTION group</u>

The solid line portrays the gain "rolloff" slope estimates, averaged over the six group members, for each run. The dashed lines correspond to one standard deviation on either side of the mean score. The subjects were provided one-to-one whole-body motion cues during runs 1 through 120. The discontinuity in the solid line between runs 80 and 81 corresponds to the point at which the other three groups were transitioned to the whole-body motion environment.

Table 5. Asymptotic model parameter estimates for tracking performance Asymptotic model parameter estimates for tracking error scores over all training (runs 1 to 80), and average tracking error scores obtained late in training (runs 65 to 80) are tabulated. The form of the asymptotic model is given by Equ.(4-1). The average asymptotic performance level for each group (tabulated below) is seen to be well within one standard deviation of average "late training" performance.

GROUP	SEX	AVERAGE LATE TRAINING SCORES (RUNS 65 to 80)	ASYMPTOTIC MODEL PARAMETERS Y_A	R	B	SUM-SQUARE ERROR FOR THE FIT
STATIC	M	6.30	6.20	.0694	4.01	30.1
STATIC	M	6.00	6.07	.0948	3.83	8.0
STATIC	M	6.13	6.16	.1125	3.61	20.2
STATIC	F	7.76	8.11	.0606	3.38	54.9
STATIC	F	6.49	6.78	.1824	3.34	16.6
STATIC	F	5.67	5.81	.2660	6.61	12.8
POSITION	M	2.77	2.83	.0826	4.27	4.9
POSITION	M	2.25	2.48	.0808	4.46	21.1
POSITION	M	3.00	3.10	.0918	3.35	8.2
POSITION	F	3.65	3.88	.0838	5.74	34.5
POSITION	F	2.89	3.32	.1035	8.68	46.8
POSITION	F	3.97	3.96	.0634	5.71	21.2
VELOCITY	M	1.74	1.81	.1028	4.29	2.9
VELOCITY	M	2.33	2.54	.1035	4.28	10.1
VELOCITY	M	2.64	2.42	.0409	4.55	9.1
VELOCITY	F	2.41	2.21	.0461	6.21	9.8
VELOCITY	F	2.46	2.62	.1046	9.86	17.5
VELOCITY	F	2.46	2.17	.0399	5.70	8.5
MOTION	M	1.99	2.12	.0839	2.22	2.4
MOTION	M	1.91	1.89	.0642	2.93	2.3
MOTION	M	1.91	1.91	.1277	1.91	1.3
MOTION	F	1.74	1.82	.1120	2.63	2.2
MOTION	F	2.35	2.38	.1168	3.03	2.5
MOTION	F	1.82	2.04	.2812	10.32	9.7

	GROUP MEANS AND STANDARD DEVIATIONS							
	RUNS 65 to 80		Y_A		R		B	
GROUP	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
STATIC	6.39	.76	6.52	.84	.1310	.08	4.13	1.24
POSITION	3.09	.62	3.26	.58	.0843	.01	5.37	1.86
VELOCITY	2.34	.34	2.30	.30	.0730	.03	5.82	2.14
MOTION	1.95	.25	2.03	.20	.1310	.08	3.84	3.20

Table 6. "Late training" tracking performance comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" rms tracking error, averaged over runs 65 through 80, which is tabulated below.

"LATE TRAINING" RMS TRACKING ERROR SCORES (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	6.30	2.77	1.74	1.99	7.76	3.65	2.41	1.74
SUBJECT 2	6.00	2.25	2.33	1.91	6.49	2.89	2.46	2.35
SUBJECT 3	6.13	3.00	2.64	1.91	5.67	3.97	2.46	1.82

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
6.39	3.09	2.34	1.95

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	73.60	3	24.53	102.90	**	.92
B	0.93	1	0.93	3.89	NS	.01
AB	0.54	3	0.18	0.75	NS	.00
WITHIN CELL	3.82	16	0.24			
TOTAL	78.89	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	3.30	**	POSITION – VELOCITY	=	0.75	NS
STATIC – VELOCITY	=	4.05	**	POSITION – MOTION	=	1.13	**
STATIC – MOTION	=	4.44	**	VELOCITY – MOTION	=	0.38	NS

(CRITICAL DIFFERENCE = 0.81 degrees)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 7. Asymptotic model parameter Y_A (asymptotic tracking performance) comparisons
This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the asymptotic rms tracking error under the training condition (model parameter "Y_A"), which was estimated using the BMD Asymptotic Regression Program (Dixon, 1973). The dependent variable is tabulated below.

RMS TRACKING ERROR ASYMPTOTES, Y_A (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	6.20	2.83	1.81	2.12	8.11	3.88	2.21	1.82
SUBJECT 2	6.07	2.48	2.54	1.89	6.78	3.32	2.62	2.38
SUBJECT 3	6.16	3.10	2.42	1.91	5.81	3.96	2.17	2.04

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
6.52	3.26	2.30	2.03

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	76.79	3	25.60	109.60	**	.92
B	1.30	1	1.30	5.56	**	.01
AB	0.85	3	0.28	1.22	NS	.00
WITHIN CELL	3.74	16	0.23			
TOTAL	82.68	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	3.26	**	POSITION – VELOCITY	=	0.97	**
STATIC – VELOCITY	=	4.22	**	POSITION – MOTION	=	1.24	**
STATIC – MOTION	=	4.49	**	VELOCITY – MOTION	=	0.27	NS

(CRITICAL DIFFERENCE = 0.80 degrees)

TUKEY'S PAIRWISE COMPARISON FOR FACTOR B (SEX)

MALE - FEMALE DIFFERENCE = –0.47 degrees **

(CRITICAL DIFFERENCE = 0.42 degrees)

** $p < 0.05$ — $F(.05;1,16) = 4.49$
NS = Not Significant — $F(.05;3,16) = 3.24$

Table 8. Asymptotic model parameter R (learning rate) comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the rms tracking error learning rate (model parameter "R"), which was estimated using the BMD Asymptotic Regression Program (Dixon, 1973). The dependent variable is tabulated below.

RMS TRACKING ERROR LEARNING RATE, R (non-dimensional)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	.069	.083	.103	.084	.061	.084	.046	.112
SUBJECT 2	.095	.081	.104	.064	.182	.104	.105	.117
SUBJECT 3	.113	.092	.041	.128	.266	.063	.040	.281

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
.131	.084	.073	.131

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	0.0168	3	0.0056	1.83	NS	.09
B	0.0068	1	0.0068	2.24	NS	.04
AB	0.0118	3	0.0039	1.29	NS	.03
WITHIN CELL	0.0490	16	0.0031			
TOTAL	0.0844	23				

** $p < 0.05$ F(.05;1,16) = 4.49

NS = Not Significant F(.05;3,16) = 3.24

Table 9. Asymptotic model parameter B (change in performance) comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the amount of change in rms tracking error during training (model parameter "B"), which was estimated using the BMD Asymptotic Regression Program (Dixon, 1973). The dependent variable is tabulated below.

CHANGE IN RMS TRACKING ERROR, B (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	4.01	4.27	4.29	2.22	3.38	5.74	6.21	2.63
SUBJECT 2	3.83	4.46	4.28	2.93	3.34	8.68	9.86	3.03
SUBJECT 3	3.61	3.35	4.55	1.91	6.61	5.71	5.70	10.32

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
4.13	5.37	5.82	3.84

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	16.35	3	5.45	1.41	NS	.04
B	31.40	1	31.40	8.10	**	.23
AB	5.59	3	1.86	0.48	NS	.00
WITHIN CELL	62.02	16	3.88			
TOTAL	115.36	23				

TUKEY'S PAIRWISE COMPARISON FOR FACTOR B (SEX)

MALE - FEMALE DIFFERENCE = –2.29 degrees **

(CRITICAL DIFFERENCE = 1.71 degrees)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 10. Asymptotic model estimate of initial performance comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the initial rms tracking error under the training condition (model parameter "$Y_A + B$"), which was estimated using the BMD Asymptotic Regression Program (Dixon, 1973). The dependent variable is tabulated below.

INITIAL RMS TRACKING ERROR, $Y_A + B$ (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	10.21	7.10	6.10	4.34	11.49	9.62	8.42	4.45
SUBJECT 2	9.90	6.94	6.82	4.82	10.12	12.00	12.48	5.41
SUBJECT 3	9.77	6.45	6.97	3.82	12.42	9.67	7.87	12.36

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
10.65	8.63	8.11	5.87

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	69.48	3	23.16	6.43	**	.33
B	45.50	1	45.50	12.64	**	.23
AB	4.11	3	1.37	0.38	NS	.00
WITHIN CELL	57.60	16	3.60			
TOTAL	176.69	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	2.02	NS	POSITION – VELOCITY	=	0.52	NS
STATIC – VELOCITY	=	2.54	NS	POSITION – MOTION	=	2.76	NS
STATIC – MOTION	=	4.78	**	VELOCITY – MOTION	=	2.24	NS

(CRITICAL DIFFERENCE = 3.15 degrees)

TUKEY'S PAIRWISE COMPARISON FOR FACTOR B (SEX)

MALE - FEMALE DIFFERENCE = –2.75 degrees **

(CRITICAL DIFFERENCE = 1.64 degrees)

** $p < 0.05$ $F(.05;1,16) = 4.49$

NS = Not Significant $F(.05;3,16) = 3.24$

Table 11. Performance changes upon transition to whole-body motion compared

This is a Type SPF-42.2 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of RUNS. Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the rms tracking error for runs 80 and 81 (i.e., the last training run and first post-transition run). The dependent variable is tabulated below.

RMS TRACKING ERROR AT TRANSITION (degrees)

	B1 = RUN 80				B2 = RUN 81			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	5.88	2.84	1.94	1.88	4.66	4.74	2.79	1.93
MALE SUBJECT 2	6.02	2.16	2.20	1.88	6.15	3.79	3.86	1.97
MALE SUBJECT 3	6.69	2.93	2.51	1.82	4.92	3.34	5.29	1.81
FEMALE SUBJECT 1	7.80	3.71	2.01	1.62	4.99	4.29	4.93	1.74
FEMALE SUBJECT 2	6.52	2.86	2.41	2.52	3.75	3.76	3.16	2.01
FEMALE SUBJECT 3	5.77	4.01	2.24	1.77	3.12	5.40	2.95	1.81
GROUP MEANS	6.45	3.09	2.22	1.92	4.60	4.22	3.83	1.88

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	82.93	3	27.64	40.63	**		.64
C	0.03	1	0.03	0.04	NS		.00
AC	2.00	3	0.67	0.98	NS		.00
Subject within Group	10.89	16	0.68				
B	0.56	1	0.56	2.03	NS	NS	.00
AB	21.38	3	7.13	25.71	**	**	.16
BC	1.28	1	1.28	4.62	**	**	.01
ABC	1.31	3	0.44	1.57	NS	NS	.00
B X Subject w. Group	4.44	16	0.28				
TOTAL	124.82	47					

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 11. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	77.93	3	25.98	54.26	**	
A at B2	26.38	3	8.80	18.37	**	
Pooled Error	15.32	32	0.48			
B at A1	10.25	1	10.25	37.00	**	**
B at A2	3.87	1	3.87	13.95	**	**
B at A3	7.82	1	7.82	28.21	**	**
B at A4	0.004	1	0.004	0.01	NS	NS
B X Subject w. Group	4.44	16	0.28			
TOTAL SSA	104.31					
TOTAL SSB	21.94					

SIGNIFICANT BC ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
C at B1	0.85	1	0.85	1.77	NS	
C at B2	0.46	1	0.46	0.97	NS	
Pooled Error	15.32	32	0.48			
B at C1	1.77	1	1.77	6.38	**	**
B at C2	0.07	1	0.07	0.26	NS	NS
B X Subject w. Group	4.44	16	0.28			
TOTAL SSB	1.84					
TOTAL SSC	1.31					

** $p < 0.05$ F(.0125;1,16) = 7.91 F(.025;1,32) = 5.53
NS = Not Significant F(0.025;1,16) = 6.12 F(.025;3,32) = 3.56

Table 11. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (RUN 80)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	3.36	**	POSITION – VELOCITY	=	0.87	NS
STATIC – VELOCITY	=	4.23	**	POSITION – MOTION	=	1.17	NS
STATIC – MOTION	=	4.53	**	VELOCITY – MOTION	=	0.31	NS

(CRITICAL DIFFERENCE = 1.34 degrees)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B2 (RUN 81)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.38	NS	POSITION – VELOCITY	=	0.39	NS
STATIC – VELOCITY	=	0.77	NS	POSITION – MOTION	=	2.34	**
STATIC – MOTION	=	2.72	**	VELOCITY – MOTION	=	1.95	**

(CRITICAL DIFFERENCE = 1.34 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF A

At A1 (STATIC TRAINING),	RUN 80 – RUN 81 Difference	=	1.85 degrees	**
At A2 (POSITION TRAINING),	RUN 80 – RUN 81 Difference	=	–1.45 degrees	**
At A3 (VELOCITY TRAINING),	RUN 80 – RUN 81 Difference	=	–1.61 degrees	**
At A4 (MOTION TRAINING),	RUN 80 – RUN 81 Difference	=	0.04 degrees	RE

(CRITICAL DIFFERENCE = 0.87 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF C

At C1 (MALE SEX), RUN 80 – RUN 81 DIFFERENCE = –0.54 degrees NS

(CRITICAL DIFFERENCE = 0.56 degrees)

** $p < 0.05$
NS = Not Significant
RE = Reference Only

Table 12. Performance of trained subjects vs. naïve subjects compared for the initial whole-body motion run

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the rms tracking error at Run 81 for the STATIC, POSITION, and VELOCITY groups, and at Run 1 for the MOTION group. The dependent variable is tabulated below.

RMS TRACKING ERROR SCORES (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	4.66	4.74	2.79	4.06	4.99	4.29	4.93	5.15
SUBJECT 2	6.15	3.79	3.86	5.44	3.75	3.76	3.16	5.69
SUBJECT 3	4.92	3.34	5.29	4.33	3.12	5.40	2.95	11.90

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
4.60	4.22	3.83	6.10

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	17.70	3	5.90	2.34	NS	.13
B	1.37	1	1.37	0.54	NS	.00
AB	14.95	3	4.98	1.97	NS	.10
WITHIN CELL	40.42	16	2.53			
TOTAL	74.44	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.38	RE	POSITION – VELOCITY	=	0.39	RE
STATIC – VELOCITY	=	0.77	RE	POSITION – MOTION	=	–1.88	RE
STATIC – MOTION	=	–1.50	RE	VELOCITY – MOTION	=	–2.27	RE

(CRITICAL DIFFERENCE = 2.62 degrees)

** p < 0.05 F(.05;1,16) = 4.49
NS = Not Significant F(.05;3,16) = 3.24
RE = Reference Only

Table 13. Tracking performance changes for all subjects compared over the final ten whole-body motion sessions

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of SEX. Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average rms tracking error for "Sessions" 21, 24, 27, and 30. The dependent variable is tabulated below.

POST-TRANSITION RMS TRACKING ERROR (degrees)

	B1 = SESSION 21				B2 = SESSION 24			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	4.19	3.84	2.63	1.90	2.10	2.55	2.23	1.88
MALE SUBJECT 2	4.62	2.91	3.18	1.95	2.96	1.78	2.35	1.85
MALE SUBJECT 3	4.16	3.00	4.30	1.84	2.95	2.12	2.96	1.71
FEMALE SUBJECT 1	4.87	3.97	3.86	1.70	3.27	3.17	2.83	1.76
FEMALE SUBJECT 2	3.87	3.55	2.88	2.10	2.46	2.05	2.70	2.11
FEMALE SUBJECT 3	2.89	4.32	3.04	1.75	2.04	2.55	2.52	1.56
GROUP MEANS	4.10	3.60	3.32	1.84	2.63	2.37	2.60	1.81

	B3 = SESSION 27				B4 = SESSION 30			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	2.11	2.37	2.27	1.96	2.10	2.19	2.14	2.20
MALE SUBJECT 2	2.13	1.69	2.24	1.82	1.87	1.65	2.05	1.87
MALE SUBJECT 3	2.55	2.15	2.28	1.71	2.28	1.96	2.21	1.71
FEMALE SUBJECT 1	2.99	2.87	2.41	1.67	2.49	2.82	2.12	1.63
FEMALE SUBJECT 2	2.16	2.11	2.27	2.06	1.84	1.73	2.30	2.19
FEMALE SUBJECT 3	1.75	2.34	2.31	1.58	1.57	1.98	2.00	1.74
GROUP MEANS	2.28	2.26	2.30	1.80	2.03	2.06	2.14	1.89

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	11.91	3	3.97	7.73	**		.19
C	0.11	1	0.11	0.22	NS		.00
AC	1.18	3	0.39	0.77	NS		.00
Subject within Group	8.21	16	0.51				
B	20.85	3	6.95	116.10	**	**	.38
AB	8.36	9	0.93	15.50	**	**	.14
BC	0.06	3	0.02	0.34	NS	NS	.00
ABC	0.36	9	0.04	0.67	NS	NS	.00
B X Subject w. Group	2.87	48	0.06				
TOTAL	53.91	95					

** $p < 0.05$ $F(.05;1,16) = 4.49$ $F(.05;3,48) = 2.80$

NS = Not Significant $F(.05;3,16) = 3.24$ $F(.05;9,48) = 2.08$

Table 13. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE						
SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	16.45	3	5.49	31.67	**	
A at B2	2.58	3	0.86	4.96	**	
A at B3	1.04	3	0.35	2.00	NS	
A at B4	0.19	3	0.06	0.37	NS	
Pooled Error	11.09	64	0.17			
B at A1	15.49	3	5.16	86.23	**	**
B at A2	8.78	3	2.93	48.90	**	**
B at A3	4.90	3	1.63	27.27	**	**
B at A4	0.04	3	0.01	0.20	NS	NS
B X Subject w. Group	2.87	48	0.06			
TOTAL SSA	20.26					
TOTAL SSB	29.21					

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.0125;3,48) = 4.02$

NS = Not Significant $F(.0125;3,64) = 3.91$

Table 13. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.50	NS	POSITION – VELOCITY	=	0.29	NS
STATIC – VELOCITY	=	0.79	NS	POSITION – MOTION	=	1.73	**
STATIC – MOTION	=	2.23	**	VELOCITY – MOTION	=	1.44	**

(CRITICAL DIFFERENCE = 0.85 degrees)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B2 (SESSION 24)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.26	NS	POSITION – VELOCITY	=	–0.23	NS
STATIC – VELOCITY	=	0.03	NS	POSITION – MOTION	=	0.56	NS
STATIC – MOTION	=	0.82	NS	VELOCITY – MOTION	=	0.79	NS

(CRITICAL DIFFERENCE = 0.85 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A1 (STATIC)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	1.47	**	SESS 24 – SESS 27	=	0.35	NS
SESS 21 – SESS 27	=	1.82	**	SESS 24 – SESS 30	=	0.61	**
SESS 21 – SESS 30	=	2.08	**	SESS 27 – SESS 30	=	0.26	NS

(CRITICAL DIFFERENCE = 0.46 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A2 (POSITION)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	1.23	**	SESS 24 – SESS 27	=	0.11	NS
SESS 21 – SESS 27	=	1.34	**	SESS 24 – SESS 30	=	0.31	NS
SESS 21 – SESS 30	=	1.54	**	SESS 27 – SESS 30	=	0.20	NS

(CRITICAL DIFFERENCE = 0.46 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A3 (VELOCITY)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	0.72	**	SESS 24 – SESS 27	=	0.30	NS
SESS 21 – SESS 27	=	1.02	**	SESS 24 – SESS 30	=	0.46	**
SESS 21 – SESS 30	=	1.18	**	SESS 27 – SESS 30	=	0.16	NS

(CRITICAL DIFFERENCE = 0.46 degrees)

** $p < 0.05$
NS = Not Significant

Table 14. Performance changes for trained subjects vs. naïve subjects compared over first ten sessions in whole-body motion

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average rms tracking error for STATIC, POSITION, and VELOCITY "Sessions" 21, 24, 27, and 30, and for MOTION "Sessions" 1, 4, 7, and 10. The dependent variable is tabulated below.

POST-TRANSITION RMS TRACKING ERROR (degrees)

	B1 = SESSION 21/1				B2 = SESSION 24/4			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	4.19	3.84	2.63	4.14	2.10	2.55	2.23	2.76
MALE SUBJECT 2	4.62	2.91	3.18	4.52	2.96	1.78	2.35	3.22
MALE SUBJECT 3	4.16	3.00	4.30	3.51	2.95	2.12	2.96	2.23
FEMALE SUBJECT 1	4.87	3.97	3.86	4.13	3.27	3.17	2.83	2.37
FEMALE SUBJECT 2	3.87	3.55	2.88	4.85	2.46	2.05	2.70	2.84
FEMALE SUBJECT 3	2.89	4.32	3.04	9.02	2.04	2.55	2.52	2.13
GROUP MEANS	4.10	3.60	3.32	5.03	2.63	2.37	2.60	2.59

	B3 = SESSION 27/7				B4 = SESSION 30/10			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	2.11	2.37	2.27	2.40	2.10	2.19	2.14	2.17
MALE SUBJECT 2	2.13	1.69	2.24	2.28	1.87	1.65	2.05	2.16
MALE SUBJECT 3	2.55	2.15	2.28	2.03	2.28	1.96	2.21	1.89
FEMALE SUBJECT 1	2.99	2.87	2.41	2.05	2.49	2.82	2.12	1.75
FEMALE SUBJECT 2	2.16	2.11	2.27	2.51	1.84	1.73	2.30	2.34
FEMALE SUBJECT 3	1.75	2.34	2.31	2.20	1.57	1.98	2.00	2.14
GROUP MEANS	2.28	2.26	2.30	2.25	2.03	2.06	2.14	2.08

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	2.69	3	0.90	1.21	NS		.00
C	0.81	1	0.81	1.09	NS		.00
AC	1.53	3	0.51	0.69	NS		.00
Subject within Group	11.81	16	0.74				
B	55.59	3	18.53	62.81	**	**	.55
AB	7.81	9	0.87	2.94	**	NS	.05
BC	0.93	3	0.31	1.05	NS	NS	.00
ABC	4.20	9	0.47	1.58	NS	NS	.02
B X Subject w. Group	14.16	48	0.30				
TOTAL	99.53	95					

** $p < 0.05$ $F(.05;1,16) = 4.49$ $F(.05;3,48) = 2.80$

NS = Not Significant $F(.05;3,16) = 3.24$ $F(.05;9,48) = 2.08$

Table 14. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21/1)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.50	RE	POSITION – VELOCITY	=	0.29	RE
STATIC – VELOCITY	=	0.79	RE	POSITION – MOTION	=	–1.43	RE
STATIC – MOTION	=	–0.93	RE	VELOCITY – MOTION	=	–1.71	RE
(CRITICAL DIFFERENCE = 1.26 degrees)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21/1 – SESS 24/4	=	1.46	**	SESS 24/4 – SESS 27/7	=	0.28	NS
SESS 21/1 – SESS 27/7	=	1.74	**	SESS 24/4 – SESS 30/10	=	0.47	**
SESS 21/1 – SESS 30/10	=	1.94	**	SESS 27/7 – SESS 30/10	=	0.20	NS
(CRITICAL DIFFERENCE = 0.42 degrees)							

** $p < 0.05$
NS = Not Significant
RE = Reference Only

Table 15. "Late training" crossover frequency comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" crossover frequency, ω_C, averaged over runs 65 through 80, which are tabulated below.

"LATE TRAINING" CROSSOVER FREQUENCY (rad/s)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	3.50	4.80	7.16	5.89	2.31	3.90	5.50	6.97
SUBJECT 2	3.37	5.91	5.84	5.96	2.51	4.57	5.26	5.02
SUBJECT 3	2.90	5.55	5.12	6.76	3.37	3.65	5.42	7.32

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
2.99	4.73	5.72	6.32

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	37.99	3	12.66	26.49	**	.73
B	2.02	1	2.02	4.22	NS	.03
AB	1.97	3	0.66	1.37	NS	.01
WITHIN CELL	7.65	16	0.48			
TOTAL	49.63	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.73	**	POSITION – VELOCITY	=	–0.99	NS
STATIC – VELOCITY	=	–2.72	**	POSITION – MOTION	=	–1.59	**
STATIC – MOTION	=	–3.32	**	VELOCITY – MOTION	=	–0.60	NS

(CRITICAL DIFFERENCE = 1.14 rad/s)

** $p < 0.05$ F(.05;1,16) = 4.49
NS = Not Significant F(.05;3,16) = 3.24

Table 16. "Late training" phase margin comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" phase margin, φ_M, averaged over runs 65 through 80, which are tabulated below.

"LATE TRAINING" PHASE MARGIN (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	17.9	20.8	18.4	18.7	36.6	26.5	21.6	16.1
SUBJECT 2	26.4	14.0	22.1	18.7	34.4	19.1	27.6	23.0
SUBJECT 3	29.1	14.1	19.3	10.5	20.3	25.0	19.5	17.1

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
27.5	19.9	21.4	17.4

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	332.7	3	110.9	4.43	**	.28
B	134.5	1	134.5	5.37	**	.12
AB	21.9	3	7.3	0.29	NS	.00
WITHIN CELL	400.9	16	25.1			
TOTAL	890.0	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	7.5	NS	POSITION – VELOCITY	=	–1.5	NS
STATIC – VELOCITY	=	6.1	NS	POSITION – MOTION	=	2.6	NS
STATIC – MOTION	=	10.1	**	VELOCITY – MOTION	=	4.1	NS

(CRITICAL DIFFERENCE = 8.3 degrees)

TUKEY'S PAIRWISE COMPARISON FOR FACTOR B (SEX)

MALE - FEMALE DIFFERENCE = –4.7 degrees **

(CRITICAL DIFFERENCE = 4.3 degrees)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 17. "Late training" open-loop gain comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" gain, K_L, averaged over runs 65 through 80, which is tabulated below.

"LATE TRAINING" GAIN (db)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	11.2	16.4	21.1	19.7	6.4	14.0	18.7	21.6
SUBJECT 2	10.0	20.1	19.6	20.0	8.3	16.7	17.9	18.4
SUBJECT 3	9.0	18.2	18.8	21.5	10.8	14.6	17.9	21.5

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
9.3	16.7	19.0	20.5

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	442.3	3	147.4	68.79	**	.87
B	14.6	1	14.6	6.81	**	.02
AB	7.8	3	2.6	1.21	NS	.00
WITHIN CELL	34.3	16	2.1			
TOTAL	499.0	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–7.38	**	POSITION – VELOCITY	=	–2.34	NS
STATIC – VELOCITY	=	–9.72	**	POSITION – MOTION	=	–3.76	**
STATIC – MOTION	=	–11.10	**	VELOCITY – MOTION	=	–1.42	NS

(CRITICAL DIFFERENCE = 2.42 db)

TUKEY'S PAIRWISE COMPARISON FOR FACTOR B (SEX)

MALE - FEMALE DIFFERENCE = 1.56 db **

(CRITICAL DIFFERENCE = 1.27 db)

** $p < 0.05$ $F(.05;1,16) = 4.49$

NS = Not Significant $F(.05;3,16) = 3.24$

Table 18. "Late training" open-loop gain slope comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" rolloff, averaged over runs 65 through 80, which is tabulated below.

"LATE TRAINING" ROLLOFF (db/decade)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	–20.9	–24.4	–26.3	–26.0	–16.6	–24.0	–25.8	–27.2
SUBJECT 2	–19.1	–27.1	–26.7	–26.5	–20.3	–25.3	–25.2	–26.6
SUBJECT 3	–19.2	–25.0	–26.9	–27.0	–20.8	–26.6	–25.2	–25.8

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
–19.5	–25.4	–26.0	–26.5

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	193.4	3	64.48	47.23	**	.86
B	1.4	1	1.38	1.01	NS	.00
AB	1.4	3	0.46	0.34	NS	.00
WITHIN CELL	21.8	16	1.37			
TOTAL	218.0	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	5.92	**	POSITION – VELOCITY	=	0.60	NS
STATIC – VELOCITY	=	6.52	**	POSITION – MOTION	=	1.11	NS
STATIC – MOTION	=	7.03	**	VELOCITY – MOTION	=	0.51	NS

(CRITICAL DIFFERENCE = 1.93 db/decade)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 19. "Late training" effective transport lag comparisons

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the "late training" effective time delay, τ_E, averaged over runs 65 through 80, which is tabulated below.

"LATE TRAINING" EFFECTIVE TIME DELAY (seconds)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	.339	.180	.105	.131	.519	.204	.134	.104
SUBJECT 2	.350	.130	.113	.123	.377	.180	.129	.130
SUBJECT 3	.388	.168	.135	.124	.342	.169	.152	.112

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
.386	.172	.128	.121

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	.2808	3	.0936	67.86	**	.90
B	.0029	1	.0029	2.14	NS	.01
AB	.0031	3	.0010	0.75	NS	.00
WITHIN CELL	.0221	16	.0014			
TOTAL	.3089	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	.214	**	POSITION – VELOCITY	=	.044	NS
STATIC – VELOCITY	=	.258	**	POSITION – MOTION	=	.051	NS
STATIC – MOTION	=	.265	**	VELOCITY – MOTION	=	.007	NS

(CRITICAL DIFFERENCE = .061 seconds)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 20. Crossover frequency changes upon transition to whole-body motion compared

This is a Type SPF-42.2 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of RUNS. Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the crossover frequency, ω_C, for runs 80 and 81 (i.e., the last training run and first post-transition run). The dependent variable is tabulated below.

	CROSSOVER FREQUENCY AT TRANSITION (rad/s)							
	B1 = RUN 80				B2 = RUN 81			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	3.57	4.53	7.24	5.67	3.80	3.85	4.80	6.18
MALE SUBJECT 2	3.28	5.70	5.46	5.60	2.90	6.27	5.66	5.80
MALE SUBJECT 3	3.08	5.61	5.32	7.08	3.39	4.98	4.59	7.14
FEMALE SUBJECT 1	2.26	3.90	6.49	7.21	2.96	6.13	3.44	6.66
FEMALE SUBJECT 2	2.67	4.77	5.39	4.97	4.27	4.09	5.15	5.48
FEMALE SUBJECT 3	3.37	3.46	5.55	7.25	5.39	5.08	5.02	7.43
GROUP MEANS	3.04	4.66	5.91	6.30	3.79	5.07	4.78	6.45

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	54.58	3	18.19	18.19	**		.57
C	0.20	1	0.20	0.20	NS		.00
AC	1.43	3	0.48	0.48	NS		.00
Subject within Group	16.01	16	1.00				
B	02	1	0.02	0.05	NS	NS	.00
AB	6.09	3	2.03	4.08	**	**	.05
BC	0.91	1	0.91	1.83	NS	NS	.00
ABC	1.90	3	0.63	1.27	NS	NS	.00
B X Subject w. Group	7.97	16	0.50				
TOTAL	89.11	47					

** $p < 0.05$ F(.05;1,16) = 4.49

NS = Not Significant F(.05;3,16) = 3.24

Table 20. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	38.91	3	12.97	17.31	**	
A at B2	21.77	3	7.26	9.69	**	
Pooled Error	23.97	32	0.75			
B at A1	1.69	1	1.69	3.39	NS	NS
B at A2	0.49	1	0.49	0.99	NS	NS
B at A3	3.86	1	3.86	7.75	NS	NS
B at A4	0.07	1	0.07	0.14	NS	NS
B X Subject w. Group	7.97	16	0.50			
TOTAL SSA	60.67					
TOTAL SSB	6.11					

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (RUN 80)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.63	NS	POSITION – VELOCITY	=	–1.25	NS
STATIC – VELOCITY	=	–2.87	**	POSITION – MOTION	=	–1.64	NS
STATIC – MOTION	=	–3.26	**	VELOCITY – MOTION	=	–0.39	NS

(CRITICAL DIFFERENCE = 1.69 rad/s)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B2 (RUN 81)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.28	NS	POSITION – VELOCITY	=	0.29	NS
STATIC – VELOCITY	=	–0.99	NS	POSITION – MOTION	=	–1.38	NS
STATIC – MOTION	=	–2.66	**	VELOCITY – MOTION	=	–1.67	NS

(CRITICAL DIFFERENCE = 1.69 rad/s)

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF A

At A1 (STATIC TRAINING),	RUN 80 – RUN 81 Difference	=	–0.75 rad/s	RE
At A2 (POSITION TRAINING),	RUN 80 – RUN 81 Difference	=	–0.41 rad/s	RE
At A3 (VELOCITY TRAINING),	RUN 80 – RUN 81 Difference	=	1.13 rad/s	RE
At A4 (MOTION TRAINING),	RUN 80 – RUN 81 Difference	=	–0.15 rad/s	RE

(CRITICAL DIFFERENCE = 1.17 rad/s)

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.025;3,32) = 3.56$
NS = Not Significant
RE = Reference Only

Table 21. Phase margin changes upon transition to whole-body motion compared

This is a Type SPF-42.2 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of RUNS. Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the phase margin, φ_M, for runs 80 and 81 (i.e., the last training run and first post-transition run). The dependent variable is tabulated below.

PHASE MARGIN AT TRANSITION (degrees)

	B1 = RUN 80				B2 = RUN 81			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	18.1	22.7	17.7	19.5	21.2	29.6	19.5	16.5
MALE SUBJECT 2	30.5	13.9	24.4	19.5	55.7	11.6	14.4	17.8
MALE SUBJECT 3	32.3	14.8	16.7	9.2	30.4	18.9	18.3	8.7
FEMALE SUBJECT 1	36.0	25.8	16.5	14.8	39.3	16.1	36.2	14.4
FEMALE SUBJECT 2	35.0	18.9	24.3	25.1	24.3	31.7	13.4	16.6
FEMALE SUBJECT 3	20.7	26.9	21.5	17.9	25.8	15.4	14.4	16.9
GROUP MEANS	28.8	20.5	20.2	17.7	32.8	20.6	19.4	15.2

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	1386.	3	461.8	6.07	**		.31
C	45.	1	44.8	0.59	NS		.00
AC	43.	3	14.3	0.19	NS		.00
Subject within Group	1217.	16	76.1				
B	0.4	1	0.4	0.01	NS	NS	.00
AB	68.	3	22.8	0.44	NS	NS	.00
BC	37.	1	36.7	0.70	NS	NS	.00
ABC	63.	3	21.1	0.41	NS	NS	.00
B X Subject w. Group	833.	16	52.0				
TOTAL	3692.	47					

** $p < 0.05$ $F(.05;1,16) = 4.49$
NS = Not Significant $F(.05;3,16) = 3.24$

Table 21. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	10.3	**	POSITION – VELOCITY	=	0.7	NS
STATIC – VELOCITY	=	11.0	**	POSITION – MOTION	=	4.1	NS
STATIC – MOTION	=	14.4	**	VELOCITY – MOTION	=	3.4	NS
(CRITICAL DIFFERENCE = 10.2 degrees)							

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF A				
At A1 (STATIC TRAINING),	RUN 80 – RUN 81 Difference	=	–3.99 degrees	RE
At A2 (POSITION TRAINING),	RUN 80 – RUN 81 Difference	=	–0.04 degrees	RE
At A3 (VELOCITY TRAINING),	RUN 80 – RUN 81 Difference	=	0.82 degrees	RE
At A4 (MOTION TRAINING),	RUN 80 – RUN 81 Difference	=	2.51 degrees	RE
(CRITICAL DIFFERENCE = 1.17 rad/s)				

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.025;3,32) = 3.56$
NS = Not Significant
RE = Reference Only

Table 22. Open-loop gain changes upon transition to whole-body motion compared

This is a Type SPF-42.2 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of RUNS. Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the low-frequency gain, K_L, for runs 80 and 81 (i.e., the last training run and first post-transition run). The dependent variable is tabulated below.

LOW-FREQUENCY GAIN AT TRANSITION (db)

	B1 = RUN 80				B2 = RUN 81			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	10.9	15.9	18.9	20.3	12.6	16.0	16.9	19.9
MALE SUBJECT 2	10.0	20.9	20.2	19.8	11.8	15.4	17.3	20.8
MALE SUBJECT 3	7.4	18.4	19.9	22.1	13.7	16.1	13.8	22.3
FEMALE SUBJECT 1	5.7	13.8	19.3	22.0	13.4	13.1	10.2	21.9
FEMALE SUBJECT 2	8.2	16.6	17.7	16.8	13.4	14.6	16.5	20.7
FEMALE SUBJECT 3	9.9	13.4	18.2	21.7	15.4	15.2	19.2	22.6
GROUP MEANS	8.7	16.5	19.0	20.5	13.4	15.1	15.7	21.4

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	604.4	3	201.5	53.64	**		.68
C	10.2	1	10.2	2.71	NS		.01
AC	14.4	3	4.8	1.28	NS		.00
Subject within Group	60.1	16	3.8				
B	0.5	1	0.5	0.12	NS	NS	.00
AB	108.9	3	36.3	9.97	**	**	.11
BC	9.1	1	9.1	2.49	NS	NS	.01
ABC	2.2	3	0.7	0.21	NS	NS	.00
B X Subject w. Group	58.2	16	3.6				
TOTAL	868.0	47					

** $p < 0.05$ F(.05;1,16) = 4.49

NS = Not Significant F(.05;3,16) = 3.24

Table 22. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	496.8	3	165.6	44.78	**	
A at B2	216.5	3	72.2	19.51	**	
Pooled Error	118.3	32	3.7			
B at A1	66.2	1	66.2	18.19	**	**
B at A2	6.1	1	6.1	1.69	NS	NS
B at A3	34.6	1	34.6	9.50	**	**
B at A4	2.4	1	2.4	0.67	NS	NS
B X Subject w. Group	58.2	16	3.6			
TOTAL SSA	713.3					
TOTAL SSB	109.4					

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (RUN 80)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–7.83	**	POSITION – VELOCITY	=	–2.52	NS
STATIC – VELOCITY	=	–10.41	**	POSITION – MOTION	=	–3.95	**
STATIC – MOTION	=	–11.80	**	VELOCITY – MOTION	=	–1.43	NS

(CRITICAL DIFFERENCE = 3.74 db)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B2 (RUN 81)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.70	NS	POSITION – VELOCITY	=	–0.56	NS
STATIC – VELOCITY	=	–2.26	NS	POSITION – MOTION	=	–6.28	**
STATIC – MOTION	=	–7.98	**	VELOCITY – MOTION	=	–5.72	**

(CRITICAL DIFFERENCE = 3.74 db)

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF A

At A1 (STATIC TRAINING),	RUN 80 – RUN 81 Difference	=	–4.7 db	**
At A2 (POSITION TRAINING),	RUN 80 – RUN 81 Difference	=	1.43 db	RE
At A3 (VELOCITY TRAINING),	RUN 80 – RUN 81 Difference	=	3.39 db	**
At A4 (MOTION TRAINING),	RUN 80 – RUN 81 Difference	=	–0.90 db	RE

(CRITICAL DIFFERENCE = 3.16 db)

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.025;3,32) = 3.56$

NS = Not Significant

RE = Reference Only

Table 23. Open-loop gain slope changes upon transition to whole-body motion compared

This is a Type SPF-42.2 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of RUNS. Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the open loop gain rolloff for runs 80 and 81 (i.e., the last training run and first post-transition run). The dependent variable is tabulated below.

OPEN LOOP GAIN ROLLOFF AT TRANSITION (db/decade)

	B1 = RUN 80				B2 = RUN 81			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	–20.0	–24.1	–23.3	–26.9	–21.5	–27.9	–24.8	–25.6
MALE SUBJECT 2	–19.7	–28.3	–27.6	–26.8	–25.6	–19.4	–23.0	–27.6
MALE SUBJECT 3	–15.8	–25.1	–27.8	–26.7	–26.7	–22.7	–21.4	–27.8
FEMALE SUBJECT 1	–15.7	–23.9	–24.5	–27.0	–26.4	–17.6	–19.4	–27.8
FEMALE SUBJECT 2	–19.8	–24.7	–24.2	–24.5	–21.3	–23.5	–23.3	–28.5
FEMALE SUBJECT 3	–18.9	–25.3	–25.1	–26.5	–21.0	–21.3	–27.4	–27.6
GROUP MEANS	–18.3	–25.2	–25.4	–26.4	–23.8	–22.1	–23.2	–27.5

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	211.5	3	70.49	24.96	**		.37
C	9.2	1	9.22	3.27	NS		.01
AC	5.8	3	1.95	0.69	NS		.00
Subject within Group	45.2	16	2.82				
B	1.0	1	0.95	0.12	NS	NS	.00
AB	135.6	3	45.22	5.48	**	**	.20
BC	0.2	1	0.16	0.02	NS	NS	.00
ABC	7.5	3	2.51	0.30	NS	NS	.00
B X Subject w. Group	132.0	16	8.25				
TOTAL	548.0	47					

** $p < 0.05$ F(.05;1,16) = 4.49

NS = Not Significant F(.05;3,16) = 3.24

Table 23. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	248.6	3	82.85	14.97	**	
A at B2	98.6	3	32.86	5.94	**	
Pooled Error	177.1	32	5.54			
B at A1	88.3	1	88.32	10.71	**	**
B at A2	30.4	1	30.35	3.68	NS	NS
B at A3	14.5	1	14.46	1.75	NS	NS
B at A4	3.5	1	3.47	0.42	NS	NS
B X Subject w. Group	132.0	16	8.25			
TOTAL SSA	347.1					
TOTAL SSB	136.6					

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (RUN 80)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	6.92	**	POSITION – VELOCITY	=	0.17	NS
STATIC – VELOCITY	=	7.09	**	POSITION – MOTION	=	1.15	NS
STATIC – MOTION	=	8.07	**	VELOCITY – MOTION	=	0.99	NS

(CRITICAL DIFFERENCE = 4.57 db/decade)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B2 (RUN 81)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.68	NS	POSITION – VELOCITY	=	1.15	NS
STATIC – VELOCITY	=	–0.53	NS	POSITION – MOTION	=	5.41	**
STATIC – MOTION	=	3.73	NS	VELOCITY – MOTION	=	4.26	NS

(CRITICAL DIFFERENCE = 4.57 db/decade)

TUKEY'S TEST FOR FACTOR B MEANS (RUN 80 VS RUN 81) AT LEVELS OF A

At A1 (STATIC TRAINING),	RUN 80 – RUN 81 Difference	=	5.43 db/decade	**
At A2 (POSITION TRAINING),	RUN 80 – RUN 81 Difference	=	–3.18 db/decade	RE
At A3 (VELOCITY TRAINING),	RUN 80 – RUN 81 Difference	=	–2.20 db/decade	RE
At A4 (MOTION TRAINING),	RUN 80 – RUN 81 Difference	=	1.08 db/decade	RE

(CRITICAL DIFFERENCE = 4.76 db/decade)

** $p < 0.05$ F(.0125;1,16) = 7.91 F(.025;3,32) = 3.56
NS = Not Significant
RE = Reference Only

Table 24. Crossover frequency for trained subjects vs. naïve subjects compared for the initial whole-body motion run

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the crossover frequency, ω_C, at Run 81 for the STATIC, POSITION, and VELOCITY groups, and at Run 1 for the MOTION group. The dependent variable is tabulated below.

CROSSOVER FREQUENCY (rad/s)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	3.80	3.85	4.80	3.59	2.96	6.13	3.44	5.01
SUBJECT 2	2.90	6.27	5.66	3.65	4.27	4.09	5.15	3.33
SUBJECT 3	3.39	4.98	4.59	4.88	5.39	5.08	5.02	1.47

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
3.79	5.07	4.78	3.66

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	8.97	3	2.99	2.64	NS	.18
B	0.04	1	0.04	0.04	NS	.00
AB	2.27	3	0.76	0.67	NS	.00
WITHIN CELL	18.15	16	1.13			
TOTAL	29.43	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.28	RE	POSITION – VELOCITY	=	0.29	RE
STATIC – VELOCITY	=	–0.99	RE	POSITION – MOTION	=	1.41	RE
STATIC – MOTION	=	0.13	RE	VELOCITY – MOTION	=	1.12	RE

(CRITICAL DIFFERENCE = 1.76 rad/s)

** $p < 0.05$ F(.05;1,16) = 4.49
NS = Not Significant F(.05;3,16) = 3.24
RE = Reference Only

Table 25. Phase margin for trained subjects vs. naïve subjects compared for the initial whole-body motion run

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the phase (stability) margin, φ_M, at Run 81 for the STATIC, POSITION, and VELOCITY groups, and at Run 1 for the MOTION group. The dependent variable is tabulated below.

PHASE (STABILITY) MARGIN (degrees)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	21.2	29.6	19.5	44.4	39.3	16.1	36.2	26.1
SUBJECT 2	55.7	11.6	14.4	41.7	24.3	31.7	13.4	35.7
SUBJECT 3	30.4	18.9	18.3	23.6	25.8	15.4	14.4	38.6

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
32.8	20.6	19.4	35.0

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	1184.	3	395.	3.52	**	.27
B	6.	1	6.	0.05	NS	.00
AB	87.	3	29.	0.26	NS	.00
WITHIN CELL	1795.	16	112.			
TOTAL	3072.	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	12.2	NS	POSITION – VELOCITY	=	1.2	NS
STATIC – VELOCITY	=	13.4	NS	POSITION – MOTION	=	–14.5	NS
STATIC – MOTION	=	–2.2	NS	VELOCITY – MOTION	=	–15.6	NS

(CRITICAL DIFFERENCE = 17.5 degrees)

** $p < 0.05$ $F(.05;1,16) = 4.49$

NS = Not Significant $F(.05;3,16) = 3.24$

Table 26. Open-loop gain for trained subjects vs. naïve subjects compared for the initial whole-body motion run

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the low-frequency gain, K_L, at Run 81 for the STATIC, POSITION, and VELOCITY groups, and at Run 1 for the MOTION group. The dependent variable is tabulated below.

LOW-FREQUENCY GAIN (db)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	12.6	16.0	16.9	11.5	13.4	13.1	10.2	14.1
SUBJECT 2	11.8	15.4	17.3	9.2	13.4	14.6	16.5	10.1
SUBJECT 3	13.7	16.1	13.8	14.0	15.4	15.2	19.2	2.2

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
13.4	15.1	15.7	10.2

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	108.0	3	36.0	4.03	**	.29
B	5.2	1	5.2	0.58	NS	.00
AB	13.4	3	4.5	0.50	NS	.00
WITHIN CELL	143.0	16	8.9			
TOTAL	269.6	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.70	NS	POSITION – VELOCITY	=	–0.56	NS
STATIC – VELOCITY	=	–2.26	NS	POSITION – MOTION	=	4.89	NS
STATIC – MOTION	=	3.19	NS	VELOCITY – MOTION	=	5.45	**

(CRITICAL DIFFERENCE = 4.95 db)

** $p < 0.05$ — $F(.05;1,16) = 4.49$

NS = Not Significant — $F(.05;3,16) = 3.24$

Table 27. Open-loop gain slope for trained subjects vs. naïve subjects compared for the initial whole-body motion run

This is a Type CRF-42 Completely Randomized Factorial Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has two levels of "SEX." The dependent variable is the open loop gain rolloff at Run 81 for the STATIC, POSITION, and VELOCITY groups, and at Run 1 for the MOTION group. The dependent variable is tabulated below.

GAIN ROLLOFF (db/decade)

	B1 = MALE				B2 = FEMALE			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
SUBJECT 1	–21.5	–27.9	–24.8	–21.0	-26.4	-17.6	-19.4	-20.2
SUBJECT 2	–25.6	–19.4	–23.0	–15.8	-21.3	-23.5	-23.3	-19.4
SUBJECT 3	–26.7	–22.7	–21.4	–20.4	-21.0	-21.3	-27.4	-18.6

POOLED GROUP MEANS

STATIC	POSITION	VELOCITY	MOTION
–23.8	–22.1	–23.2	–19.2

ANALYSIS OF VARIANCE TABLE FOR TYPE CRF-42 DESIGN

SOURCE	SS	DF	MS	F RATIO		SOA
A	73.1	3	24.4	2.73	NS	.19
B	5.0	1	5.0	0.56	NS	.00
AB	9.4	3	3.1	0.35	NS	.00
WITHIN CELL	142.6	16	8.9			
TOTAL	230.1	23				

TUKEY'S PAIRWISE COMPARISONS FOR FACTOR A (DRIVE LAW)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.68	RE	POSITION – VELOCITY	=	1.15	RE
STATIC – VELOCITY	=	–0.53	RE	POSITION – MOTION	=	–2.83	RE
STATIC – MOTION	=	–4.52	RE	VELOCITY – MOTION	=	–3.98	RE

(CRITICAL DIFFERENCE = 4.93 db/decade)

** $p < 0.05$
NS = Not Significant
RE = Reference Only

$F(.05;1,16) = 4.49$
$F(.05;3,16) = 3.24$

Table 28. Crossover frequency changes for all subjects compared over the final ten whole-body motion sessions

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average crossover frequency, ω_C, for "Sessions" 21, 24, 27, and 30. The dependent variable is tabulated below.

POST-TRANSITION CROSSOVER FREQUENCY (rad/s)

	B1 = SESSION 21				B2 = SESSION 24			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	4.05	3.96	5.00	6.02	6.48	5.06	5.55	6.41
MALE SUBJECT 2	4.41	5.78	5.79	5.91	5.63	7.13	6.01	6.52
MALE SUBJECT 3	4.04	5.62	4.21	6.89	5.95	6.78	5.03	7.33
FEMALE SUBJECT 1	3.06	5.22	4.21	6.67	3.89	4.34	5.11	6.71
FEMALE SUBJECT 2	3.83	4.55	5.01	5.43	5.33	5.75	4.75	5.41
FEMALE SUBJECT 3	5.56	4.34	5.16	7.38	6.44	5.15	5.63	7.32
GROUP MEANS	4.16	4.91	4.90	6.38	5.62	5.70	5.35	6.62
	B3 = SESSION 27				B4 = SESSION 30			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	6.20	5.46	5.69	6.26	5.33	6.23	6.02	5.96
MALE SUBJECT 2	6.45	6.94	5.65	6.57	6.98	6.96	5.80	6.46
MALE SUBJECT 3	6.69	6.68	5.52	7.06	6.19	6.79	6.06	7.12
FEMALE SUBJECT 1	4.79	4.72	5.52	6.73	5.30	4.67	5.58	7.02
FEMALE SUBJECT 2	5.69	5.64	5.63	5.45	6.53	6.40	5.70	5.31
FEMALE SUBJECT 3	7.22	5.76	6.15	7.41	7.18	6.32	6.48	7.48
GROUP MEANS	6.17	5.87	5.69	6.58	6.25	6.23	5.94	6.56

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	17.41	3	5.80	3.04	NS		.13
C	2.56	1	2.56	1.35	NS		.01
AC	2.65	3	0.88	0.46	NS		.00
Subject within Group	30.50	16	1.91				
B	18.78	3	6.26	44.32	**	**	.21
AB	7.59	9	0.84	5.97	**	**	.07
BC	1.19	3	0.40	2.80	**	NS	.01
ABC	0.70	9	0.08	0.55	NS	NS	.00
B X Subject w. Group	6.78	48	0.14				
TOTAL	88.16	95					

** $p < 0.05$ $F(.05;1,16) = 4.49$ $F(.05;3,48) = 2.80$

NS = Not Significant $F(.05;3,16) = 3.24$ $F(.05;9,48) = 2.08$

Table 28. (continued)

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	15.65	3	5.22	8.96	**	
A at B2	5.49	3	1.83	3.14	NS	
A at B3	2.72	3	0.91	1.56	NS	
A at B4	1.14	3	0.38	0.65	NS	
Pooled Error	37.28	64	0.58			
B at A1	16.94	3	5.65	39.98	**	**
B at A2	5.55	3	1.85	13.10	**	**
B at A3	3.69	3	1.23	8.70	**	**
B at A4	0.19	3	0.06	0.46	NS	NS
B X Subject w. Group	6.78	48	0.14			
TOTAL SSA	25.00					
TOTAL SSB	26.38					

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

** p < 0.05 F(.0125;1,16) = 7.91 F(.0125;3,48) = 4.02
NS = Not Significant F(.0125;3,64) = 3.91

Table 28. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–0.75	NS	POSITION – VELOCITY	=	0.02	NS
STATIC – VELOCITY	=	–0.74	NS	POSITION – MOTION	=	–1.47	NS
STATIC – MOTION	=	–2.22	**	VELOCITY – MOTION	=	–1.49	NS
(CRITICAL DIFFERENCE = 1.57 rad/s)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A1 (STATIC)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–1.46	**	SESS 24 – SESS 27	=	–0.56	NS
SESS 21 – SESS 27	=	–2.01	**	SESS 24 – SESS 30	=	–0.64	NS
SESS 21 – SESS 30	=	–2.09	**	SESS 27 – SESS 30	=	–0.08	NS
(CRITICAL DIFFERENCE = 0.71 rad/s)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A2 (POSITION)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–0.79	**	SESS 24 – SESS 27	=	–0.17	NS
SESS 21 – SESS 27	=	–0.96	**	SESS 24 – SESS 30	=	–0.53	NS
SESS 21 – SESS 30	=	–1.32	**	SESS 27 – SESS 30	=	–0.36	NS
(CRITICAL DIFFERENCE = 0.71 rad/s)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A3 (VELOCITY)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–0.45	NS	SESS 24 – SESS 27	=	–0.35	NS
SESS 21 – SESS 27	=	–0.80	**	SESS 24 – SESS 30	=	–0.59	NS
SESS 21 – SESS 30	=	–1.04	**	SESS 27 – SESS 30	=	–0.25	NS
(CRITICAL DIFFERENCE = 0.71 rad/s)							

** $p < 0.05$
NS = Not Significant

Table 29. Phase margin changes for all subjects compared over the final ten whole-body motion sessions

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average phase (stability) margin, φ_M, for "Sessions" 21, 24, 27, and 30. The dependent variable is tabulated below.

POST-TRANSITION PHASE MARGIN (degrees)

	B1 = SESSION 21				B2 = SESSION 24			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	21.6	29.7	19.4	18.4	15.4	21.1	17.4	17.1
MALE SUBJECT 2	38.5	19.0	17.0	18.9	25.5	16.0	18.0	15.4
MALE SUBJECT 3	24.4	17.1	26.1	10.3	16.3	13.5	19.0	9.2
FEMALE SUBJECT 1	39.8	19.8	27.3	17.9	38.4	27.0	19.2	18.4
FEMALE SUBJECT 2	29.1	23.0	16.9	18.8	20.3	17.6	22.7	20.4
FEMALE SUBJECT 3	21.8	22.0	14.9	15.4	15.3	24.9	16.6	16.3
GROUP MEANS	29.2	21.8	20.3	16.6	21.9	20.0	18.8	16.1

	B3 = SESSION 27				B4 = SESSION 30			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	14.9	17.0	17.9	18.3	22.8	14.0	16.1	20.3
MALE SUBJECT 2	18.6	16.4	25.1	16.0	17.0	16.9	17.5	16.5
MALE SUBJECT 3	11.5	13.8	16.7	10.4	15.2	14.2	15.3	10.5
FEMALE SUBJECT 1	25.6	23.6	17.3	18.6	22.0	23.4	17.0	16.2
FEMALE SUBJECT 2	18.7	16.1	15.5	19.7	13.7	17.3	15.6	22.2
FEMALE SUBJECT 3	11.9	19.8	13.3	16.9	11.4	15.0	14.9	16.4
GROUP MEANS	16.9	17.8	17.6	16.7	17.0	16.8	16.1	17.0

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	269.6	3	90.0	1.35	NS		.02
C	82.0	1	82.0	1.23	NS		.01
AC	78.7	3	26.2	0.39	NS		.00
Subject within Group	1068.0	16	66.8				
B	404.8	3	134.9	13.12	**	**	.13
AB	347.3	9	38.6	3.75	**	**	.09
BC	58.8	3	19.6	1.91	NS	NS	.01
ABC	66.7	9	7.4	0.72	NS	NS	.00
B X Subject w. Group	493.5	48	10.3				
TOTAL	2869.4	95					

** $p < 0.05$ F(.05;1,16) = 4.49 F(.05;3,48) = 2.80
NS = Not Significant F(.05;3,16) = 3.24 F(.05;9,48) = 2.08

Table 29. (continued)

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	503.7	3	167.9	6.88	**	
A at B2	103.9	3	34.6	1.42	NS	
A at B3	5.6	3	1.9	0.08	NS	
A at B4	3.6	3	1.2	0.05	NS	
Pooled Error	1561.0	64	24.4			
B at A1	603.2	3	201.1	19.56	**	**
B at A2	89.4	3	29.8	2.90	NS	NS
B at A3	57.1	3	19.0	1.85	NS	NS
B at A4	2.4	3	0.8	0.08	NS	NS
B X Subject w. Group	493.5	48	10.3			
TOTAL SSA	616.9					
TOTAL SSB	752.1					

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	7.4	NS	POSITION – VELOCITY	=	1.5	NS
STATIC – VELOCITY	=	8.9	NS	POSITION – MOTION	=	5.2	NS
STATIC – MOTION	=	12.6	**	VELOCITY – MOTION	=	3.7	NS

(CRITICAL DIFFERENCE = 10 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A1 (STATIC)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	7.3	**	SESS 24 – SESS 27	=	5.0	NS
SESS 21 – SESS 27	=	12.3	**	SESS 24 – SESS 30	=	4.8	NS
SESS 21 – SESS 30	=	12.2	**	SESS 27 – SESS 30	=	–0.2	NS

(CRITICAL DIFFERENCE = 6.0 degrees)

** $p < 0.05$ F(.0125;1,16) = 7.91 F(.0125;3,48) = 4.02
NS = Not Significant F(.0125;3,64) = 3.91

Table 30. Open-loop gain changes for all subjects compared over the final ten whole-body motion sessions

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average low-frequency gain, K_L, for "Sessions 21, 24, 27, and 30. The dependent variable is tabulated below.

POST-TRANSITION LOW-FREQUENCY GAIN (db)

	B1 = SESSION 21				B2 = SESSION 24			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	14.2	15.2	17.4	19.8	19.3	16.9	19.1	20.6
MALE SUBJECT 2	15.2	17.3	17.3	20.6	16.3	20.9	20.1	20.4
MALE SUBJECT 3	14.1	17.6	14.5	21.8	18.1	20.0	17.0	22.4
FEMALE SUBJECT 1	11.5	14.4	13.2	21.5	14.3	15.1	16.1	20.1
FEMALE SUBJECT 2	13.4	16.1	16.8	19.8	18.7	20.7	16.1	19.0
FEMALE SUBJECT 3	16.1	15.2	19.1	22.3	18.8	18.6	19.2	22.1
GROUP MEANS	14.1	16.0	16.4	21.0	17.6	18.7	17.9	20.8

	B3 = SESSION 27				B4 = SESSION 30			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	21.3	19.0	18.7	19.5	19.4	20.5	19.1	18.2
MALE SUBJECT 2	20.4	22.5	19.1	20.8	20.1	22.4	20.8	20.2
MALE SUBJECT 3	19.3	19.9	19.7	22.5	19.4	20.8	21.4	22.7
FEMALE SUBJECT 1	15.6	15.9	18.6	21.1	17.5	16.2	20.0	21.1
FEMALE SUBJECT 2	18.8	21.5	19.2	19.3	20.7	22.1	19.1	18.3
FEMALE SUBJECT 3	21.4	18.8	20.5	22.1	22.2	19.6	20.7	22.0
GROUP MEANS	19.5	19.6	19.3	20.9	19.9	20.3	20.2	20.4

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	122.0	3	40.66	3.84	**		.15
C	11.5	1	11.54	1.09	NS		.00
AC	7.1	3	2.35	0.22	NS		.00
Subject within Group	169.3	16	10.58				
B	161.4	3	53.81	58.95	**	**	.26
AB	80.2	9	8.91	9.76	**	**	.12
BC	1.3	3	0.44	0.48	NS	NS	.00
ABC	6.9	9	0.77	0.84	NS	NS	.00
B X Subject w. Group	43.8	48	0.91				
TOTAL	603.5	95					

** $p < 0.05$ F(.05;1,16) = 4.49 F(.05;3,48) = 2.80
NS = Not Significant F(.05;3,16) = 3.24 F(.05;9,48) = 2.08

Table 30. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE

SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	154.9	3	51.6	15.50	**	
A at B2	37.0	3	12.3	3.70	NS	
A at B3	9.4	3	3.1	0.94	NS	
A at B4	0.9	3	0.3	0.09	NS	
Pooled Error	213.2	64	3.3			
B at A1	127.4	3	42.5	46.52	**	**
B at A2	63.9	3	21.3	23.34	**	**
B at A3	49.3	3	16.4	18.00	**	**
B at A4	1.1	3	0.3	0.38	NS	NS
B X Subject w. Group	43.8	48	0.9			
TOTAL SSA	202.2					
TOTAL SSB	241.6					

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.0125;3,48) = 4.02$
NS = Not Significant $F(.0125;3,64) = 3.91$

Table 30. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.92	NS	POSITION – VELOCITY	=	–0.41	NS
STATIC – VELOCITY	=	–2.33	NS	POSITION – MOTION	=	–5.00	**
STATIC – MOTION	=	–6.92	**	VELOCITY – MOTION	=	–4.59	**

(CRITICAL DIFFERENCE = 3.74 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A1 (STATIC)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–3.52	**	SESS 24 – SESS 27	=	–1.90	**
SESS 21 – SESS 27	=	–5.42	**	SESS 24 – SESS 30	=	–2.31	**
SESS 21 – SESS 30	=	–5.83	**	SESS 27 – SESS 30	=	–0.42	NS

(CRITICAL DIFFERENCE = 1.79 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A2 (POSITION)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–2.72	**	SESS 24 – SESS 27	=	–0.90	NS
SESS 21 – SESS 27	=	–3.62	**	SESS 24 – SESS 30	=	–1.57	NS
SESS 21 – SESS 30	=	–4.29	**	SESS 27 – SESS 30	=	–0.67	NS

(CRITICAL DIFFERENCE = 1.79 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A3 (VELOCITY)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–1.56	NS	SESS 24 – SESS 27	=	–1.36	NS
SESS 21 – SESS 27	=	–2.92	**	SESS 24 – SESS 30	=	–2.23	**
SESS 21 – SESS 30	=	–3.79	**	SESS 27 – SESS 30	=	–0.87	NS

(CRITICAL DIFFERENCE = 1.79 db)

** $p < 0.05$
NS = Not Significant

Table 31. Open-loop gain slope changes for all subjects compared over the final ten whole-body motion sessions

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average open-loop gain rolloff for "Sessions" 21, 24, 27, and 30. The dependent variable is tabulated below.

POST-TRANSITION GAIN ROLLOFF (db/decade)

	B1 = SESSION 21				B2 = SESSION 24			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	-23.0	-25.5	-25.1	-26.0	-24.6	-24.3	-25.7	-26.8
MALE SUBJECT 2	-24.2	-22.8	-23.1	-27.5	-21.4	-26.0	-26.5	-26.3
MALE SUBJECT 3	-23.6	-23.2	-23.3	-27.4	-23.4	-25.4	-24.4	-27.3
FEMALE SUBJECT 1	-23.5	-20.8	-21.3	-27.1	-24.4	-23.5	-23.0	-25.1
FEMALE SUBJECT 2	-23.1	-24.3	-24.1	-27.5	-26.3	-26.7	-23.8	-26.5
FEMALE SUBJECT 3	-22.1	-24.1	-27.4	-26.8	-23.5	-26.8	-26.6	-26.4
GROUP MEANS	-23.3	-23.5	-24.1	-27.1	-23.9	-25.5	-25.0	-26.4

	B3 = SESSION 27				B4 = SESSION 30			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	-28.0	-26.2	-24.6	-25.2	-27.4	-26.9	-25.0	-24.1
MALE SUBJECT 2	-26.3	-28.2	-26.2	-26.6	-24.7	-27.6	-27.9	-26.3
MALE SUBJECT 3	-23.9	-25.1	-26.8	-28.1	-24.7	-25.8	-28.5	-28.3
FEMALE SUBJECT 1	-23.2	-24.0	-25.4	-26.7	-24.4	-24.3	-27.3	-25.8
FEMALE SUBJECT 2	-25.2	-29.4	-25.7	-26.7	-26.0	-28.4	-25.3	-25.6
FEMALE SUBJECT 3	-25.6	-25.1	-27.3	-26.3	-27.0	-25.3	-27.3	-26.5
GROUP MEANS	-25.4	-26.3	-26.0	-26.6	-25.7	-26.4	-26.9	-26.1

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	46.79	3	15.60	3.19	NS		.11
C	1.23	1	1.23	0.25	NS		.00
AC	0.24	3	0.08	0.02	NS		.00
Subject within Group	78.20	16	4.89				
B	51.33	3	17.11	12.29	**	**	.16
AB	37.52	9	4.17	2.99	**	NS	.08
BC	0.63	3	0.21	0.15	NS	NS	.00
ABC	11.36	9	1.26	0.91	NS	NS	.00
B X Subject w. Group	66.82	48	1.39				
TOTAL	294.12	95					

** $p < 0.05$ $F(.05;1,16) = 4.49$ $F(.05;3,48) = 2.80$
NS = Not Significant $F(.05;3,16) = 3.24$ $F(.05;9,48) = 2.08$

Table 31. (continued)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	0.73	NS	SESS 24 – SESS 27	=	0.90	NS
SESS 21 – SESS 27	=	1.63	**	SESS 24 – SESS 30	=	1.09	**
SESS 21 – SESS 30	=	1.83	**	SESS 27 – SESS 30	=	0.20	NS
(CRITICAL DIFFERENCE = 0.91 db/decade)							

** $p < 0.05$
NS = Not Significant

Table 32. Crossover frequency changes for trained subjects vs. naïve subjects compared over first ten sessions in whole-body motion

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average crossover frequency ω_C, for STATIC, POSITION, and VELOCITY "Sessions" 21, 24, 27, and 30, and for MOTION "Sessions" 1, 4, 7, and 10. The dependent variable is tabulated below.

POST-TRANSITION CROSSOVER FREQUENCY (rad/s)

	B1 = SESSION 21/1				B2 = SESSION 24/2			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	4.05	3.96	5.00	3.69	6.48	5.06	5.55	5.41
MALE SUBJECT 2	4.41	5.78	5.79	3.80	5.63	7.13	6.01	4.64
MALE SUBJECT 3	4.04	5.62	4.21	5.36	5.95	6.78	5.03	6.01
FEMALE SUBJECT 1	3.06	5.22	4.21	4.75	3.89	4.34	5.11	5.89
FEMALE SUBJECT 2	3.83	4.55	5.01	3.65	5.33	5.75	4.75	4.75
FEMALE SUBJECT 3	5.56	4.34	5.16	2.23	6.44	5.15	5.63	6.10
GROUP MEANS	4.16	4.91	4.90	3.91	5.62	5.70	5.35	5.47

	B3 = SESSION 27/7				B4 = SESSION 30/10			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	6.20	5.46	5.69	5.48	5.33	6.23	6.02	5.58
MALE SUBJECT 2	6.45	6.94	5.65	5.75	6.98	6.96	5.80	6.04
MALE SUBJECT 3	6.69	6.68	5.52	6.43	6.19	6.79	6.06	6.54
FEMALE SUBJECT 1	4.79	4.72	5.52	6.64	5.30	4.67	5.58	6.63
FEMALE SUBJECT 2	5.69	5.64	5.63	5.06	6.53	6.40	5.70	5.12
FEMALE SUBJECT 3	7.22	5.76	6.15	7.12	7.18	6.32	6.48	6.09
GROUP MEANS	6.17	5.87	5.69	6.08	6.25	6.23	5.94	6.00

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	1.25	3	0.42	0.25	NS		.00
C	2.72	1	2.72	1.64	NS		.01
AC	2.51	3	0.84	0.50	NS		.00
Subject within Group	26.64	16	1.67				
B	39.20	3	13.07	54.55	**	**	.42
AB	5.20	9	0.58	2.41	**	NS	.03
BC	0.40	3	0.14	0.56	NS	NS	.00
ABC	2.40	9	0.27	1.11	NS	NS	.00
B X Subject w. Group	11.50	48	0.24				
TOTAL	91.82	95					

** $p < 0.05$	$F(.05;1,16) = 4.49$	$F(.05;3,48) = 2.80$
NS = Not Significant	$F(.05;3,16) = 3.24$	$F(.05;9,48) = 2.08$

Table 32. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21/1)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–0.75	RE	POSITION – VELOCITY	=	0.01	RE
STATIC – VELOCITY	=	–0.74	RE	POSITION – MOTION	=	1.00	RE
STATIC – MOTION	=	0.25	RE	VELOCITY – MOTION	=	0.99	RE
(CRITICAL DIFFERENCE = 1.59 rad/s)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–1.06	**	SESS 24 – SESS 27	=	–0.42	**
SESS 21 – SESS 27	=	–1.48	**	SESS 24 – SESS 30	=	–0.57	**
SESS 21 – SESS 30	=	–1.64	**	SESS 27 – SESS 30	=	–0.15	NS
(CRITICAL DIFFERENCE = 0.37 rad/s)							

** $p < 0.05$
NS = Not Significant
RE = Reference Only

Table 33. Phase margin changes for trained subjects vs. naïve subjects compared over first ten sessions in whole-body motion

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average phase (stability) margin, φ_M, for STATIC, POSITION, and VELOCITY "Sessions" 21, 24, 27, and 30, and for MOTION "Sessions" 1, 4, 7, and 10. The dependent variable is tabulated below.

POST-TRANSITION PHASE MARGIN (degrees)

	B1 = SESSION 21/1				B2 = SESSION 24/4			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	21.6	29.7	19.4	44.2	15.4	21.1	17.4	22.3
MALE SUBJECT 2	38.5	19.0	17.0	42.7	25.5	16.0	18.0	29.0
MALE SUBJECT 3	24.4	17.1	26.1	18.5	16.3	13.5	19.0	16.7
FEMALE SUBJECT 1	39.8	19.8	27.3	23.7	38.4	27.0	19.2	15.3
FEMALE SUBJECT 2	29.1	23.0	16.9	32.4	20.3	17.6	22.7	22.8
FEMALE SUBJECT 3	21.8	22.0	14.9	33.7	15.3	24.9	16.6	19.8
GROUP MEANS	29.2	21.8	20.3	32.5	21.9	20.0	18.8	21.0

	B3 = SESSION 27/7				B4 = SESSION 30/10			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	14.9	17.0	17.9	22.6	22.8	14.0	16.1	20.4
MALE SUBJECT 2	18.6	16.4	25.1	19.4	17.0	16.9	17.5	18.3
MALE SUBJECT 3	11.5	13.8	16.7	13.5	15.2	14.2	15.3	13.9
FEMALE SUBJECT 1	25.6	23.6	17.3	14.6	22.0	23.4	17.0	15.8
FEMALE SUBJECT 2	18.7	16.1	15.5	19.4	13.7	17.3	15.6	22.0
FEMALE SUBJECT 3	11.9	19.8	13.3	17.0	11.4	15.0	14.9	17.8
GROUP MEANS	16.9	17.8	17.6	17.8	17.0	16.8	16.1	18.0

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	258.7	3	86.2	1.03	NS		.00
C	6.9	1	6.9	0.08	NS		.00
AC	130.0	3	43.3	0.52	NS		.00
Subject within Group	1340.0	16	83.7				
B	1213.0	3	404.2	28.03	**	**	.28
AB	407.4	9	45.3	3.14	**	NS	.07
BC	40.0	3	13.3	0.92	NS	NS	.00
ABC	109.5	9	12.2	0.84	NS	NS	.00
B X Subject w. Group	692.2	48	14.4				
TOTAL	4197.7	95					

** $p < 0.05$ $F(.05;1,16) = 4.49$ $F(.05;3,48) = 2.80$

NS = Not Significant $F(.05;3,16) = 3.24$ $F(.05;9,48) = 2.08$

Table 33. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21/1)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	7.4	RE	POSITION – VELOCITY	=	1.5	RE
STATIC – VELOCITY	=	8.9	RE	POSITION – MOTION	=	–10.7	RE
STATIC – MOTION	=	–3.3	RE	VELOCITY – MOTION	=	–12.2	RE

(CRITICAL DIFFERENCE = 11.5 degrees)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	5.5	**	SESS 24 – SESS 27	=	2.9	NS
SESS 21 – SESS 27	=	8.4	**	SESS 24 – SESS 30	=	3.4	**
SESS 21 – SESS 30	=	9.0	**	SESS 27 – SESS 30	=	0.5	NS

(CRITICAL DIFFERENCE = 2.9 degrees)

** $p < 0.05$
NS = Not Significant
RE = Reference Only

Table 34. Open-loop gain changes for trained subjects vs. naïve subjects compared over first ten sessions in whole-body motion

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average low-frequency gain, K_L, for STATIC, POSITION, and VELOCITY "Sessions" 21, 24, 27, and 30, and for MOTION "Sessions" 1, 4, 7, and 10. The dependent variable is tabulated below.

POST-TRANSITION LOW-FREQUENCY GAIN (db)

	B1 = SESSION 21/1				B2 = SESSION 24/4			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	14.2	15.2	17.4	10.9	19.3	16.9	19.1	16.3
MALE SUBJECT 2	15.2	17.3	17.3	10.7	16.3	20.9	20.1	13.9
MALE SUBJECT 3	14.1	17.6	14.5	15.2	18.1	20.0	17.0	18.4
FEMALE SUBJECT 1	11.5	14.4	13.2	14.8	14.3	15.1	16.1	17.9
FEMALE SUBJECT 2	13.4	16.1	16.8	10.9	18.7	20.7	16.1	15.7
FEMALE SUBJECT 3	16.1	15.2	19.1	8.6	18.8	18.6	19.2	19.9
GROUP MEANS	14.1	16.0	16.4	11.9	17.6	18.7	17.9	17.0

	B3 = SESSION 27/7				B4 = SESSION 30/10			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	21.3	19.0	18.7	17.3	19.4	20.5	19.1	18.9
MALE SUBJECT 2	20.4	22.5	19.1	18.0	20.1	22.4	20.8	19.1
MALE SUBJECT 3	19.3	19.9	19.7	20.3	19.4	20.8	21.4	21.4
FEMALE SUBJECT 1	15.6	15.9	18.6	20.4	17.5	16.2	20.0	20.5
FEMALE SUBJECT 2	18.8	21.5	19.2	17.6	20.7	22.1	19.1	17.6
FEMALE SUBJECT 3	21.4	18.8	20.5	19.2	22.2	19.6	20.7	20.0
GROUP MEANS	19.5	19.6	19.3	18.8	19.9	20.3	20.2	19.6

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	48.65	3	16.22	1.45	NS		.02
C	9.12	1	9.12	0.82	NS		.00
AC	9.76	3	3.25	0.29	NS		.00
Subject within Group	179.10	16	11.19				
B	417.40	3	139.10	103.50	**	**	.53
AB	41.52	9	4.61	3.43	**	**	.04
BC	0.42	3	0.14	0.10	NS	NS	.00
ABC	12.29	9	1.37	1.02	NS	NS	.00
B X Subject w. Group	64.52	48	1.34				
TOTAL	782.78	95					

** $p < 0.05$ F(.05;1,16) = 4.49 F(.05;3,48) = 2.80

NS = Not Significant F(.05;3,16) = 3.24 F(.05;9,48) = 2.08

Table 34. (continued)

SIGNIFICANT AB ANALYSIS OF VARIANCE TABLE						
SOURCE	SS	DF	MS	F RATIO	CONV	CONS
A at B1	77.59	3	25.86	6.80	**	
A at B2	8.79	3	2.93	0.77	NS	
A at B3	2.14	3	0.71	0.19	NS	
A at B4	1.66	3	0.55	0.15	NS	
Pooled Error	243.60	64	3.81			
B at A1	127.40	3	42.46	31.59	**	**
B at A2	63.91	3	21.30	15.85	**	**
B at A3	49.29	3	16.43	12.22	**	**
B at A4	218.30	3	72.77	54.14	**	**
B X Subject w. Group	64.52	48	1.34			
TOTAL SSA	90.17					
TOTAL SSB	458.90					

** $p < 0.05$ $F(.0125;1,16) = 7.91$ $F(.0125;3,48) = 4.02$

NS = Not Significant $F(.0125;3,64) = 3.91$

Table 34. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21/1)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	–1.92	NS	POSITION – VELOCITY	=	–0.41	NS
STATIC – VELOCITY	=	–2.33	NS	POSITION – MOTION	=	4.12	**
STATIC – MOTION	=	2.21	NS	VELOCITY – MOTION	=	4.54	**

(CRITICAL DIFFERENCE = 3.97 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A1 (STATIC)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–3.52	**	SESS 24 – SESS 27	=	–1.90	NS
SESS 21 – SESS 27	=	–5.42	**	SESS 24 – SESS 30	=	–2.31	**
SESS 21 – SESS 30	=	–5.83	**	SESS 27 – SESS 30	=	–0.42	NS

(CRITICAL DIFFERENCE = 2.18 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A2 (POSITION)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–2.72	**	SESS 24 – SESS 27	=	–0.90	NS
SESS 21 – SESS 27	=	–3.62	**	SESS 24 – SESS 30	=	–1.57	NS
SESS 21 – SESS 30	=	–4.29	**	SESS 27 – SESS 30	=	–0.67	NS

(CRITICAL DIFFERENCE = 2.18 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A3 (VELOCITY)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–1.56	NS	SESS 24 – SESS 27	=	–1.36	NS
SESS 21 – SESS 27	=	–2.92	**	SESS 24 – SESS 30	=	–2.23	**
SESS 21 – SESS 30	=	–3.79	**	SESS 27 – SESS 30	=	–0.87	NS

(CRITICAL DIFFERENCE = 2.18 db)

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS) AT A4 (MOTION)

MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	–5.18	**	SESS 24 – SESS 27	=	–1.78	NS
SESS 21 – SESS 27	=	–6.96	**	SESS 24 – SESS 30	=	–2.56	**
SESS 21 – SESS 30	=	–7.74	**	SESS 27 – SESS 30	=	–0.78	NS

(CRITICAL DIFFERENCE = 2.18 db)

** $p < 0.05$
NS = Not Significant

Table 35. Open-loop gain slope changes for trained subjects vs. naïve subjects compared over first ten sessions in whole-body motion

This is a Type SPF-42.4 Split Plot Design. Factor A has four levels of "DRIVE LAW" (STATIC, POSITION, VELOCITY, AND MOTION). Factor B has four levels of "SESSIONS." Factor C has two levels of "SEX." Subjects (blocks) within each group received all levels of B, but only one level of A and C. The dependent variable is the session average open-loop gain rolloff for STATIC, POSITION, and VELOCITY "Sessions" 21, 24, 27, and 30, and for MOTION "Sessions" 1, 4, 7, and 10. The dependent variable is tabulated below.

POST-TRANSITION GAIN ROLLOFF (db/decade)

	B1 = SESSION 21/1				B2 = SESSION 24/4			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	–23.0	–25.5	–25.1	–19.3	–24.6	–24.3	–25.7	–22.2
MALE SUBJECT 2	–24.2	–22.8	–23.1	–18.6	–21.4	–26.0	–26.5	–21.0
MALE SUBJECT 3	–23.6	–23.2	–23.3	–20.1	–23.4	–25.4	–24.4	–23.3
FEMALE SUBJECT 1	–23.5	–20.8	–21.3	–21.9	–24.4	–23.5	–23.0	–24.1
FEMALE SUBJECT 2	–23.1	–24.3	–24.1	–20.0	–26.3	–26.7	–23.8	–23.4
FEMALE SUBJECT 3	–22.1	–24.1	–27.4	–27.6	–23.5	–26.8	–26.6	–25.8
GROUP MEANS	–23.3	–23.5	–24.1	–21.3	–23.9	–25.5	–25.0	–23.3

	B3 = SESSION 27/7				B4 = SESSION 30/10			
	A1=S	A2=P	A3=V	A4=M	A1=S	A2=P	A3=V	A4=M
MALE SUBJECT 1	–28.0	–26.2	–24.6	–23.7	–27.4	–26.9	–25.0	–25.5
MALE SUBJECT 2	–26.3	–28.2	–26.2	–23.8	–24.7	–27.6	–27.9	–25.1
MALE SUBJECT 3	–23.9	–25.1	–26.8	–26.1	–24.7	–25.8	–28.5	–26.7
FEMALE SUBJECT 1	–23.2	–24.0	–25.4	–26.0	–24.4	–24.3	–27.3	–26.1
FEMALE SUBJECT 2	–25.2	–29.4	–25.7	–25.4	–26.0	–28.4	–25.3	–25.1
FEMALE SUBJECT 3	–25.6	–25.1	–27.3	–23.2	–27.0	–25.3	–27.3	–25.9
GROUP MEANS	–25.4	–26.3	–26.0	–24.7	–25.7	–26.4	–26.9	–25.7

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-42.2 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	47.09	3	15.70	2.96	NS		.07
C	1.24	1	1.24	0.23	NS		.00
AC	14.81	3	4.94	0.93	NS		.00
Subject within Group	84.98	16	5.31				
B	143.30	3	47.76	25.05	**	**	.33
AB	10.84	9	1.20	0.63	NS	NS	.00
BC	6.43	3	2.14	1.12	NS	NS	.00
ABC	19.44	9	2.16	1.13	NS	NS	.01
B X Subject w. Group	91.53	48	1.91				
TOTAL	419.66	95					

** $p < 0.05$ — $F(.05;1,16) = 4.49$ — $F(.05;3,48) = 2.80$

NS = Not Significant — $F(.05;3,16) = 3.24$ — $F(.05;9,48) = 2.08$

Table 35. (continued)

TUKEY'S TEST FOR FACTOR A MEANS (DRIVE LAW) AT B1 (SESSION 21/1)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
STATIC – POSITION	=	0.20	RE	POSITION – VELOCITY	=	0.60	RE
STATIC – VELOCITY	=	0.80	RE	POSITION – MOTION	=	–2.20	RE
STATIC – MOTION	=	–2.00	RE	VELOCITY – MOTION	=	–2.80	RE
(CRITICAL DIFFERENCE = 3.29 db/decade)							

TUKEY'S TEST FOR FACTOR B MEANS (SESSIONS)							
MEAN(I) – MEAN(J)	=	DIFFERENCE		MEAN(I) – MEAN(J)	=	DIFFERENCE	
SESS 21 – SESS 24	=	1.42	**	SESS 24 – SESS 27	=	1.20	**
SESS 21 – SESS 27	=	2.61	**	SESS 24 – SESS 30	=	1.77	**
SESS 21 – SESS 30	=	3.19	**	SESS 27 – SESS 30	=	0.57	NS
(CRITICAL DIFFERENCE = 1.07 db/decade)							

** $p < 0.05$
NS = Not Significant
RE = Reference Only

CHAPTER 5

Summary

This report describes the research conducted to determine whether information which was tactually displayed through a seat pan could be interpreted and used as motion information. The experiment was designed such that the transfer of training from the tactual seat-pan display to a whole-body motion environment could also be evaluated. The experimental tracking task required subjects to maintain a “wings-level” attitude in a vehicle having aircraft-like dynamics while the vehicle was being perturbed about the roll axis by a random-appearing disturbance. Subjects were divided into four training groups: (1) STATIC (visual information only), (2) POSITION (visual plus tactual cues via a POSITION “Drive Law”), (3) VELOCITY (visual plus tactual cues via a VELOCITY “Drive Law”), and (4) MOTION (visual in a one-to-one motion environment). The experiment was conducted in two phases, a training phase and a criterion phase. During training, the four groups tracked under their respective training conditions. During the criterion phase, all groups tracked in the criterion whole-body motion device. Data collected late in the training phase were used to evaluate the effectiveness of the tactual display. The criterion phase provided data for the evaluation of the transfer of training.

Table 36 provides a summary of “late training” mean scores and the results of pairwise comparison tests on the scores of the four groups. The key results obtained from the training data are the following.

1. An effective time delay reduction of 0.21 to 0.27 seconds was observed for the groups provided motion information (i.e., the POSITION, VELOCITY, and MOTION groups). All time delay differences relative to the STATIC group are significant.

2. The groups provided motion information tracked with lower phase (stability) margins than did the STATIC group. However, only the STATIC-MOTION difference was large enough to be statistically significant.

3. The reduction in effective time delay and phase margins permitted the operators provided with motion information to increase their gain, and hence crossover frequency; a higher

order gain "rolloff" was also observed. All differences relative to the STATIC group are significant.

4. Rms tracking errors for the POSITION, VELOCITY, and MOTION groups were lower than that of the STATIC group as a result of the higher low-frequency gain facilitated by the motion information. All differences relative to the STATIC group are significant.

5. Tracking performance and control behavior for operators presented VELOCITY "Drive Law" motion information were statistically indistinguishable from those of a similar group of operators tracking in a one-to-one whole-body motion environment. Scores for operators provided POSITION "Drive Law" seat-pan cues were detectably different from the MOTION group for three variables: tracking error, crossover frequency, and gain; however, POSITION group scores were significantly better than STATIC group scores for these three variables.

6. Normalized open-loop remnant referred to the operator's input did not materially differ among the groups (Section 4.3.3)—however there was one notable trend. The VELOCITY group exhibited higher values of mid-frequency remnant than did the others (suggesting higher mid-frequency observation or signal processing noise for this group). At higher frequencies there were no differences of any practical significance among the groups' remnant power characteristics.

An implication drawn from (5) and (6) above together with comparisons of the Human Operator Describing Functions (Section 4.3.3), is that a blend of the POSITION and VELOCITY "Drive Laws" may be more effective than either drive law alone for controlled plant dynamics like those used in this experiment. A suitable "Drive Law" may be one in which VELOCITY information is "washed in" to the POSITION "Drive Law" at higher frequencies so as to provide a "quickened" tactual seat-pan display (e.g., see Fig. 6-37 in Frost, 1972). Further research is recommended to determine whether a "Drive Law" filter of this form does lead to a better match of both the linear and stochastic portions of the Human Operator Describing Function. Relationships between the appropriate filter time constant (and/or filter structure) and the controlled plant dynamics also need to be determined.

Table 36. Comparison of group scores for the static, tactual seat-pan motion display, and whole-body motion conditions

(Detailed information is provided in the Referenced Tables.)

	LATE TRAINING MEAN SCORES				SIGNIFICANCE OF DIFFERENCES IN THE GROUPS' MEAN SCORES						REFERENCE TABLE
	S	P	V	M	S-P	S-V	S-M	P-V	P-M	V-M	
TRACKING ERROR (degrees)	6.4	3.1	2.3	2.0	**	**	**	NS	**	NS	(6)
CROSSOVER FREQUENCY (rad/s)	3.0	4.7	5.7	6.3	**	**	**	NS	**	NS	(15)
PHASE MARGIN (degrees)	28.	20.	21.	17.	NS	NS	**	NS	NS	NS	(16)
OPEN-LOOP GAIN (db)	9.	17.	19.	21.	**	**	**	NS	**	NS	(17)
GAIN ROLLOFF (db/decade)	-20	-25	-26	-27	**	**	**	NS	NS	NS	(18)
EFFECTIVE TIME DELAY (seconds)	.39	.17	.13	.12	**	**	**	NS	NS	NS	(19)

** $p < 0.05$
NS = Not Significant
S = STATIC Group (visual information only)
P = POSITION Group (visual plus Position Drive Law tactual cues)
V = VELOCITY Group (visual plus Velocity Drive Law tactual cues)
M = MOTION Group (visual in a one-to-one whole-body motion environment)

It is concluded that motion information can be effectively imparted through a dynamic seat tactual display. However, a need for more research regarding the use of a dynamic seat as a training device is indicated. Despite the degree to which both the performance and control behavior of dynamic seat subjects mimicked those of the MOTION group during training, dynamic seat training did not carry over to the full motion environment well. Upon transition to the criterion whole-body motion device, tracking errors were statistically indistinguishable between the STATIC, POSITION, and VELOCITY groups. Moreover, comparisons of early full motion scores for the STATIC, POSITION, and VELOCITY trained subjects to the early training scores of MOTION subjects did not show much intrinsic benefit of training (Sections 4.2.6, 4.3.6, and 4.4).

While the general lack of transfer was disappointing, it was not surprising. The motion environment of the dynamic seat simulator was subjectively very much different from that of the criterion device; the seat did not induce a percept of self motion. The extent to which this lack of "realism" detracted from the analogy needed for good transfer (Gregory, 1976) is not known. The information necessary for the accomplishment of the tracking task was provided through the seat, but seat cues did not substantially help subjects develop the associations needed to interpret and use the motion cues in the criterion device. On the other hand, the observed trends do suggest that training with seat cues was more beneficial than training in a static environment; the dynamic seat's potential utility as a training device should not be ruled out. Further research is needed to establish whether there may be a "Drive Law" more optimal for training than those used in this experiment. The dynamic seat should also be evaluated within the context of a full scale flight simulator to determine whether the interaction of seat cues with a richer visual and/or moving platform environment may enhance its training utility. Finally, the findings of this research, which drew upon subjects from a non-pilot population, should eventually be validated using subjects drawn from a population of experienced pilots.

Regardless of its utility as a training device, the dynamic seat can effectively display motion information. This suggests the potential utility of a dynamic seat in engineering research and development simulators where it is important that the pilot adopt a control style in the simulator equivalent to that adopted in the aircraft. Accordingly, it is recommended that further research be carried out to extend the results of this roll-axis study to other degrees of freedom. Another possible role is the use of a dynamic seat as a means of tactually communicating information to the operator of a vehicle. An advantage offered by a tactual seat display is that the operator would normally be in contact with it; this may not be true for tactual displays integrated into control sticks or wheels. The extent to which vehicle motion might interfere with the tactually displayed information is unknown, and needs to be empirically determined.

In sum, the data in this report clearly demonstrate that tactual cues provided via a dynamic seat pan can be effectively used as motion information. It appears that a tactual display of this type could be useful in research and development simulators or for communicating information to the operator of a vehicle. The results of the training transfer portion of this study were not so encouraging, however, and indicated that the dynamic seat (as used in this investigation) was not adequate for training naïve subjects to properly interpret and use the motion information available in the whole-body motion environment. Additional research is needed to fully evaluate the potential of a dynamic seat as a training device.

EPILOGUE

Given the disappointing training transfer observed upon transition from the dynamic seat to the RATS, it was decided to see whether a "Drive Law" based upon the subjective equivalence of the motion experienced in the dynamic seat to that experienced in the whole-body motion environment of the RATS would improve the situation. A new "Drive Law" was independently derived using a cross-modality tracking task in a procedure designated "Subjective Interactive Gain Measurement Analysis (SIGMA)." In this procedure subjects were presented the visual display illustrated in Fig. 3, wherein the aircraft symbol oscillated sinusoidally about the roll-axis at a fixed amplitude and single frequency. Subjects then adjusted motion in both the RATS and dynamic seat so that it was subjectively oscillating at the same amplitude as the visual reference; this was done for two different amplitudes at six different frequencies. Flach et al., (1985) derived a frequency domain "Drive Law" based on a fit to the average data from six subjects. The resulting "Drive Law" was a first-order lead with a gain of 0.67 and a break frequency at 6 rad/s—remarkably close to the POSITION "Drive Law" transitioning to a VELOCITY "Drive Law" in the neighborhood of 4 rad/s derived from observation of the VELOCITY group's remnant in section 4.3.3. Unfortunately, while late training behavior and performance with this "Drive Law" was similar to that observed in later RATS sessions, transition to the RATS was worse than that observed with the POSITION and VELOCITY groups.

Up to this point all studies were conducted with naïve (i.e., non-pilot) subjects. A follow-on study using the SIGMA "Drive Law" reported by McMillan et al., (1985) and Martin et al., (1986) did find a significant improvement in training transfer when using (eight) experienced pilots as subjects. This suggests that, in addition to eliciting whole-body-motion-like performance and control behavior in the training environment, dynamic seats may provide a positive training benefit when used with a population of experienced pilots (as would normally be the case). Future training research should focus on experienced pilots to better define capabilities and requirements in this regard.

Osgood (1988) extended the ALCOGS experimentation from the roll-axis to the pitch-axis using an aerial refueling task wherein the four subjects controlling a fighter-dynamics aircraft simulation were provided a visual representation of a KC-135 tanker. The subjects were instructed to maintain pitch attitude in the presence of a random-appearing pitch disturbance. The objective measure was rms pitch error. The objective of this study was to evaluate four different seat-pan and backrest configurations to determine the best configuration for pitch axis cuing. A combination seat-pan and backrest with the two joined at the rear of the seat pan (i.e., moving as a single unit) was the recommended configuration.

A later pitch-axis study was conducted at AFAMRL using outer loop variables (e.g., pitch attitude and altitude) as metrics. These turned out to be relatively insensitive to motion information, and did not lead to any significant findings. In the late 1990s, the ALCOGS was moved to an Air Vehicles Directorate facility at Wright-Patterson AFB where a series of ALCOGS-based studies sponsored by the Training Systems Product Group were conducted. These focused on developing drive algorithms for F-16 flight simulators. While a subjectively effective pitch-axis drive algorithm that could handle full loops was reportedly discovered, it was never subjected to objective empirical tests and the drive algorithm was never documented nor implemented in a training device. No further ALCOGS experiments have been conducted since that time.

BIBLIOGRAPHY

Albery, W.B., D.R. Gum, and G.J. Kron, 1978. Motion and Force Cuing Requirements and Techniques for Advanced Tactical Aircraft Simulation. AGARD Piloted Aircraft Environment Simulation Techniques Conference Proceedings. AGARD-CP-249, NTIS, Springfield VA.

Ashworth, B.R., 1976. A Seat Cushion to Provide Realistic Acceleration Cues for Aircraft Simulators. NASA TM X-73954, NASA Langley Research Center, Hampton VA.

Ashworth, B.R., B.T. McKissick, and R.V. Parrish, 1979. The Effects of Simulation Fidelity on Air-to-Air Tracking. 15th Annual Conference on Manual Control, Wright State University, Dayton OH.

Ashworth, B.R., B.T. McKissick, and R.V. Parrish, 1984. Effects of Motion Base and G-seat Cueing on Simulator Pilot Performance. NASA TP-2247, NASA Langley Research Center, Hampton VA.

Baron, S., R. Muralidharan, and D. Kleinman, 1980. Closed Loop Models for Analyzing Engineering Requirements for Simulators. NASA CR-2965, NASA Langley Research Center, Hampton VA.

Boneau, C.A., 1960. The Effects of Violations of Assumptions Underlying the t Test. Psychological Bulletin 37(1): 49-64.

Borah, J., L.R. Young, and R.E. Curry, 1977. Sensory Mechanism Modeling (Interim Report). Tech. Rept. No. AFHRL-TR-77-70, AFHRL, Brooks AFB TX.

Borah, J., L.R. Young, and R.E. Curry, 1979. Sensory Mechanism Modeling (Final Report). Tech. Rept. No. AFHRL-TR-78-83, AFHRL, Brooks AFB TX.

Bose, E.B., W.P. Leavy, and S. Ramachandran, 1981. Improved G-cueing System. AIAA Flight Simulation Technologies Conference, Long Beach CA.

Brown, C.D., 1978. Current Deficiencies in Simulation for Training. AGARD Piloted Aircraft Environment Simulation Techniques Conference Proceedings. AGARD-CP-249, NTIS, Springfield VA.

Clark, F.J., and K.W. Horch, 1986. Kinesthesia. In K. Boff, L. Kaufman, and J. Thomas (Ed.) *Handbook of Perception and Human Performance*. New York NY: John Wiley.

Craig, J.C., and C.E. Sherrick, 1982. Dynamic Tactile Displays. In W. Schiff and E. Foulke (Ed.) Tactual Perception: A Sourcebook. New York NY: Cambridge University Press.

D'Azzo, J.J., and C.H. Houpis, 1966. Feedback Control System Analysis and Synthesis. New York NY: McGraw-Hill.

Dixon, W.J. (Ed.), 1973. BMD Biomedical Computer Programs. 3rd ed., Los Angeles CA: University of California Press.

Eveleigh, V.W., 1967. Adaptive Control and Optimization Techniques. New York NY: McGraw-Hill.

Federal Aviation Administration, Dept. of Transportation, 1980. Advanced Simulation. Federal Register 45(127): 44176-44186, Washington DC: Government Printing Office.

Flach, J.M., G.R. McMillan, and R. Warren, 1985. The Effects of Psychophysical Matching on the Transfer of Training between Alternative Motion Simulators. Third Symposium on Aviation Psychology, Ohio State University, Columbus OH.

Frost, G., 1972. Man-Machine Dynamics. In H.P. Van Cott and R.G. Kinkade (Ed.) Human Engineering Guide to Equipment Design. Revised Edition, Chapter 6, Washington DC: Government Printing Office.

Geddes, L.A., and L.E. Baker, 1975. Principles of Applied Biomedical Instrumentation. New York NY: John Wiley.

Gold, B., and C.M. Rader, 1969. Digital Processing of Signals. New York NY: McGraw-Hill.

Goldstein, H., 1965. Classical Mechanics. Reading MA: Addison-Wesley.

Gregory, R.L., 1976. The Display Problem of Flight Simulation. Proceedings of the 3rd Flight Simulation Symposium—Theory and Practice in Flight Simulation, Royal Aeronautical Society, London.

Gum, D.R., 1973. Modeling of the Human Force and Motion Sensing Mechanisms. Tech. Rept. No. AFHRL-TR-72-54, AFHRL, Brooks AFB TX.

Hall, J.R., 1978. Motion Versus Visual Cues in Piloted Flight Simulation. AGARD Piloted Aircraft Environment Simulation Techniques Conference Proceedings. AGARD-CP-249, NTIS, Springfield VA.

Hays, W.L., 1963. Statistics for Psychologists. New York NY: Holt, Rinehart and Winston.

Hill, J.W., 1970. A Describing Function Analysis of Tracking Performance Using Two Tactile Displays. IEEE Transactions on Man-Machine Systems MMS-11(1): 92-101.

Hosman, R.J.A.W., and J.C. van der Vaart, 1981. Effects of Vestibular and Visual Motion Perception on Task Performance. Acta Psychologica 48: 271-287.

Howe, R.M., R.L. Bowles, J.C. Dusterberry, R.E. Flexman, E.R. Jones, C.L. Kraft, R.V. Parrish, R.W. Pew, M.L. Ritchie, J.B. Sinacori, D.B. Ynetma, D.A. Beam, 1978. Report of the USAF Scientific Advisory Board Ad Hoc Committee on Simulation Technology. Department of the Air Force, Washington, DC.

Jaeger, R.J., G.C. Agarwal, and Gottlieb, 1979. Predictor Operator in Pursuit and Compensatory Tracking. 15th Annual Conference on Manual Control, Wright State University, Dayton OH.

Jagacinski, R.J., J.M. Flach, and R.D. Gilson, 1983. A Comparison of Visual and Kinesthetic-Tactual Displays for Compensatory Tracking. IEEE Transactions on Systems, Man, and Cybernetics SMC-13: 1103-1112.

Jex, H.R., 1971. Interfacing Man-Machine Control Performance in a Biodynamic Environment. Symposium on Biodynamic Models and their Applications, October 26-28, 1970, Tech. Rept. No. AMRL-TR-71-29, AFAMRL, Wright-Patterson AFB OH.

Jex, H.R., R.E. Magdaleno, W.F. Jewell, A. Junker, and G. McMillan, 1981. Effects on Target Tracking of Motion Simulator Drive-Logic Filters. Tech. Rept. No. AFAMRL-TR-80-134, AFAMRL, Wright-Patterson AFB OH.

Junker, A.M., and W.H. Levison, 1977. Use of the Optimal Control Pilot Model in the Design of Experiments. 13th Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge MA.

Key, D.L., B.L. Odneal, and J.B. Sinacori, 1978. Mission Environment Simulation for Army Rotorcraft Development—Requirements and Capabilities. AGARD Piloted Aircraft Environment Simulation Techniques Conference Proceedings. AGARD-CP-249, NTIS, Springfield VA.

Kirk, R.E., 1968. Experimental Design: Procedures for the Behavioral Sciences. Belmont CA: Brooks/Cole.

Kirk, R.E., 1982. Experimental Design: Procedures for the Behavioral Sciences. 2nd ed., Belmont CA: Brooks/Cole.

Kleinman, D.L., S. Baron, and W.H. Levison, 1969. An Optimal Control Model of Human Behavior. 5th Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge MA. (NASA SP-215)

Kleinman, D.L., S. Baron, and W.H. Levison, 1971. A Control Theoretic Approach to Manned-Vehicle Systems Analysis. IEEE Transactions on Automatic Control AC-16: 824-832.

Kleinwaks, J.M., 1980. Advanced Low Cost G-Cuing System (ALCOGS). Tech. Rept. No. AFHRL-TR-79-62, AFHRL, Brooks AFB TX.

Kron, G.J., 1975. Advanced Simulation in Undergraduate Pilot Training: G-seat Development. Tech. Rept. No. AFHRL-75-59(III), AFHRL, Brooks AFB TX.

Kron, G.J., and J.M. Kleinwaks, 1978. Development of the Advanced G-Cueing System. AIAA Paper No. 78-1572.

Levison, W.H., S. Baron, and D.L. Kleinman, 1969. A Model for Human Controller Remnant. IEEE Transactions on Man-Machine Systems MMS-10: 101-108.

Levison, W.H., 1975. Techniques for Data Analysis and Input Waveform Generation for Manual Control Research. Tech. Memo. No. CSD-75-2, Bolt Beranek and Newman, Cambridge MA.

Levison, W.H., S. Baron, and A.M. Junker, 1976. Modeling the Effects of Environmental Factors on Human Control and Information Processing. Tech. Rept. No. AMRL-TR-76-74 (AD A-030585), AFAMRL, Wright-Patterson AFB OH.

Levison, W.H., and A.M. Junker, 1977. A Model for the Pilot's Use of Motion Cues in Roll-Axis Tracking Tasks. Tech. Rept. No. AMRL-TR-77-40, AFAMRL, Wright-Patterson AFB OH.

Levison, W.H., and G.L. Zacharias, 1977. Modeling the Pilot's Use of Motion Cues During Transient Aircraft Maneuvers. Tech. Rept. No. 3676, Bolt Beranek and Newman, Cambridge MA.

Levison, W.H., R.E. Lancraft, and A.M. Junker, 1979. Effects of Simulator Delays on Performance and Learning in a Roll-Axis Tracking Task. 15th Annual Conference on Manual Control, Wright State University, Dayton OH.

Levison, W.H., 1982. Methods for Identifying Pilot Dynamics. Proceedings of the Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics, Tech. Rept. No. AFFTC-TR-82-5, Edwards AFB CA.

Levison, W.H., 1983. Development of a Model for Human Operator Learning in Continuous Estimation and Control Tasks. Tech. Rept. No. AMRL-TR-83-088, AFAMRL, Wright-Patterson AFB OH.

Levison, W.H., and S. Baron, 1984. F-14 Modeling Study. NASA CR-172336, NASA Langley Research Center, Hampton VA.

Levison, W.H., G.R. McMillan, and E.A. Martin, 1984. Models for the Effects of G-seat Cuing on Roll-axis Tracking Performance. 20th Annual Conference on Manual Control, NASA Ames Research Center, Moffett Field CA.

Loomis, J.M., and S.J. Lederman, 1986. Tactual Perception. In K. Boff, L. Kaufman, and J. Thomas (Ed.) *Handbook of Perception and Human Performance*. New York NY: John Wiley.

Martin, E.A., G.R. McMillan, R. Warren, and G.E. Riccio, 1986. A Program to Investigate Requirements for Effective Flight Simulator Displays. Proceedings of the International Conference on Advances in Flight Simulation Visual and Motion Systems, The Royal Aeronautical Society, London W1, UK.

Matthews, N.O., and C.A. Martin, 1978. The Development and Evaluation of a G-seat for a High Performance Military Aircraft Training Simulator. AGARD Piloted Aircraft Environment Simulation Techniques Conference Proceedings. AGARD-CP-249, NTIS, Springfield VA.

McGuire, D.C., and D.R. Lee, 1979. Advanced Simulator for Pilot Training (ASPT): G-seat Optimization. Tech. Rept. No. AFHRL-TR-78-92, AFHRL, Brooks AFB TX.

McMillan, G.R., E.A. Martin, J.M. Flach, and G.E. Riccio, 1985. Advanced Dynamic Seats: An Alternative to Platform motion? 7th Interservice/Industry Training Equipment Conference (I/ITEC), Orlando FL.

McMillan, G.R., W.H. Levison, and E.A. Martin, 1984. Motion Simulation with a G-seat System: Sensory and Performance Mechanisms. 9th Psychology in DOD Symposium, U.S. Air Force Academy, Colorado Springs CO.

McRuer, D.T., and E.S. Krendel, 1957. Dynamic Response of Human Operators. Tech. Rept. No. WADC-TR-56-524, Wright-Patterson AFB OH.

McRuer, D.T., D. Graham, E. Krendel, and W. Reisener, 1965. Human Pilot Dynamics in Compensatory Systems—Theory, Models, and Experiments with Controlled Element and Forcing Function Variations. Tech. Rept. No. AFFDL-TR-65-15 (AD 470337), Wright-Patterson AFB OH.

McRuer, D., 1966. Some Neuromuscular Dynamics. 2nd Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge MA. (NASA SP-128)

McRuer, D.T., and H.R. Jex, 1967. A Review of Quasi-Linear Pilot Models. IEEE Transactions on Human Factors in Electronics HFE-8(3): 231-249.

Meiry, J.L., 1965. The Vestibular System and Human Dynamic Space Orientation. Sc. D. Thesis, Massachusetts Institute of Technology, Cambridge MA (NASA CR-628.)

Milsum, J.H., 1966. Biological Control Systems Analysis. New York NY: McGraw-Hill.

Neter, J., and W. Wasserman, 1974. Applied Linear Statistical Models. Homewood IL: Richard D. Irwin.

Oosterveld, W.J., D.L. Key, G.P. Bates, R. Bray, W.S. Chambers, H. Friedrich, C.A. Gainer, N. Hammer, W. Koevermans, J.M. Rolfe, Shulz-Helbach, J.F. Smith, K. Staples, and L.R. Young, 1980. Fidelity of Simulation for Pilot Training. AGARD-AR-159 (AD A-096825), NTIS, Springfield VA.

Osgood, R.K., 1988. Pitch Cuing in the Dynamic Seat: An Exploratory Study. Technical Memorandum TM-87-RKO-001, AAMRL, Human Engineering Division, Wright-Patterson AFB OH.

Parrish, R.V., and G.G. Steinmetz, 1983. Evaluation of G-seat Augmentation of Fixed-base/Moving-base Simulation for Transport Landings Under Two Visually Imposed Runway Width Conditions. NASA TP-2135, NASA Langley Research Center, Hampton VA.

Puig, J.A., W.T. Harris, and G.L. Ricard, 1978. Motion in Flight Simulation: An Annotated Bibliography. Tech. Rept. No. NAVTRAEQUIPCEN IH-298, NTEC, Orlando FL.

Reising, J.M., S.L. Ward, and E.P. Rolek, 1977. Some Thoughts on Improving Experiments. Human Factors 19(3): 221-226.

Ringland, R.F., and R.L. Stapleford, 1971. Motion Cue Effects on Pilot Tracking. 7th Annual Conference on Manual Control, University of Southern California, Los Angeles CA.

Rosko, J.S., 1972. Digital Simulation of Physical Systems. Reading MA: Addison-Wesley.

Schmid, H.P., and G.A. Bekey, 1978. Tactile Information Processing by Human Operators in Control Systems. IEEE Transactions on Systems, Man, and Cybernetics SMC-8: 860-866.

Sherrick, C.E., and R.W. Cholewiak, 1986. Cutaneous Sensitivity. In K. Boff, L. Kaufman, and J. Thomas (Ed.) *Handbook of Perception and Human Performance*. New York NY: John Wiley.

Shirley, R.S., 1968. Motion Cues in Man-Vehicle Control. M.I.T. Rept. No. MVT-68-1 (Sc. D. Thesis), Massachusetts Institute of Technology, Cambridge MA.

Showalter, T.W., 1978. A Pilot Evaluation of Two G-seat Cueing Schemes. NASA TP-1255, NASA Ames Research Center, Moffett Field CA.

Showalter, T.W., and B.L. Parris, 1980. The Effects of Motion and G-seat Cues on Pilot Simulator Performance of Three Piloting Tasks. NASA TP-1601, NASA Ames Research Center, Moffett Field CA.

Stapleford, R.L., R.A. Peters, and F.R. Alex, 1969. Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs. NASA CR-1325.

Staples, K.L., 1978. Current Problems of Flight Simulators for Research. The Aeronautical Journal: 12-32.

Stark, L., 1968. Neurological Control Systems, Studies in Bioengineering. New York NY: Plenum Press.

Stevens, W.L., 1951. Asymptotic Regression. Biometrics 7(3): 247-267.

Truxal, J.G., 1955. Automatic Feedback Control System Analysis. New York NY: McGraw-Hill.

Young, L.R., C.M. Oman, R.E. Curry, and J.M. Dichgans, 1973. A Descriptive Model of Multi-sensor Human Spatial Orientation with Applications to Visually Induced Sensations of Motion. AIAA Paper No. 73-915, presented at Palo Alto CA.

Young, L.R., 1982. Human Orientation in Space. AIAA Dryden Lecture in Research.

Zacharias, G.L., 1978. Motion Cue Models for Pilot-Vehicle Analysis. Tech. Rept. No. AMRL-TR-78-2, AFAMRL, Wright-Patterson AFB OH.

Zacharias, G.L., and W.H. Levison, 1978. A Performance Analyzer for Identifying Changes in Human Operator Tracking Strategies. Tech. Rept. No. 3910, Bolt Beranek and Newman, Cambridge MA.

Zacharias, G.L., and W.H. Levison, 1979. A Performance Analyzer for Identifying Changes in Human Operator Tracking Strategies. 15th Annual Conference on Manual Control, Wright State University, Dayton OH. (Abridged version of Zacharias and Levison, 1978)

GLOSSARY OF ACRONYMS AND SYMBOLS

ACRONYMS

ADC	Analog-to-digital converter
AFAMRL	Air Force Aerospace Medical Research Laboratory
AFHRL	Air force Human Resources Laboratory
AGARD	North Atlantic Treaty Organization (NATO) Advisory Group for Aerospace Research and Development
ALCOGS	Advanced Low Cost G-cuing System
ANOVA	Analysis of Variance
CONS	Conservative F-Test, where the F ratio degrees-of-freedom are reduced
CONV	Conventional F-Test, with unmodified degrees-of-freedom
CRF	Completely Randomized Factorial
DAC	Digital-to-analog converter
DF	Degrees-of-freedom
HODF	Human Operator Describing Function
LPF	Low-pass filter
MS	Mean square value
NASA	National Aeronautical and Space Administration
NTEC	Naval Training Equipment Center
NTIS	National Technical Information Service
RATS	Roll-Axis Tracking Simulator
RBF	Randomized Block Factorial
RMS	Root mean square value
SD	Standard deviation
SOA	Strength of association—the estimated proportion of the variance accounted for by the independent variable
SPF	Split Plot Factorial
SS	Sum square value
ZOH	Zero-Order-Hold

SYMBOLS

B	Asymptotic model parameter corresponding to the amount of change in score with training
c(t)	Operator control action (output)
C(jω)	Transform of operator control action (output)
d(t)	Disturbance forcing function
D(jω)	Transform of disturbance forcing function
db	Decibel
deg	Degree
e(t)	Roll error signal for the system
E(jω)	Transform of roll error signal
$F(df_1,df_2)$	F ratio with numerator degrees-of-freedom df_1 and denominator degrees-of-freedom df_2
$F(p;df_1,df_2)$	F distribution percentiles with numerator degrees-of-freedom df_1 and denominator degrees-of-freedom df_2, defined as follows: Probability $\{F(df_1,df_2) < F(p;df_1,df_2))\} = 1-p$
g	Gravitation constant
H(jω)	Operator steady-state frequency domain describing function
HV(jω)	Open-loop operator-controlled plant steady-state frequency domain describing function
Hz	Hertz—frequency in cycles per second
j	Square root of (-1)
K	Gain factor associated with dynamic seat drive laws
K_L	Open loop gain (db) at 1 rad/s
lb	Pound-force
ms	Millisecond
p	Level at which the risk that a Type I error (i.e., finding a difference in means when in fact there is none) may be committed by chance is controlled
p	RATS cab roll velocity (rad/s)
p(t)	Controlled plant (vehicle) position
P(jω), P(s)	Transform of controlled plant position
psi	Pounds per square inch

$r(t)$	Operator remnant
R	Asymptotic model parameter corresponding to the estimated rate of learning
rad/s	Radians per second
s	Laplace operator
s	Seconds
SF	Specific Force (g-units)—external non-gravitational force acting on a body, per unit mass of that body
t	Time
$u(t)$	Summed rate command input to the controlled plant
$U(j\omega)$, $U(s)$	Transform of summed rate command input to the controlled plant
$V(j\omega)$	Controlled plant (vehicle) steady-state frequency domain transfer function
$\mathrm{var}(\cdot)$	Variance of $(\cdot)$
Y_A	Asymptotic model parameter corresponding to the estimate for asymptotic performance score
τ_E	Effective time delay or transport lag (seconds)
φ_C	Open loop phase angle (degrees) at ω_C
φ_M	Phase margin (degrees)—allowable phase lag increase for incipient loop instability
$\Phi(\omega)$	Operator remnant power spectral density
ω	Angular velocity (frequency) in rad/s
ω_C	Crossover frequency (rad/s)—frequency corresponding to 0 db open-loop gain (this sets the effective bandwidth of the closed-loop system)
$\lvert(\cdot)\rvert$	Magnitude of $(\cdot)$
$/\underline{(\cdot)}$	Phase angle of $(\cdot)$
$(\cdot)'$	Time derivative of $(\cdot)$

APPENDIX A

Development of a Seat Cuing Drive Law

A.1 Background

The paucity of data and lack of any generally accepted methodology for displaying motion information via a dynamic seat (Albery et al., 1978; Showalter, 1978) necessitated preliminary work to design a viable seat cuing "Drive Law" before an experiment to investigate the utility of a roll-axis seat cuing device could be carried out. The tendency of most G-seat investigators to focus upon the display of sustained, normal acceleration cues (Albery et al., 1978; Ashworth, 1976; Matthews and Martin, 1978) coupled with the failure of researchers who did investigate roll-axis cuing to find a satisfactory "Drive Law" either in terms of "proper feel" (Showalter, 1978) or usefulness of the displayed information (Showalter and Parris, 1980) further exacerbated the roll-axis cuing problem. Given the absence of any firm guidelines, it was postulated that an appropriate way to drive the seat would be in such fashion as to produce body-seat contact pressures similar to those which would be experienced in the whole-body motion environment. Such an approach was in fact suggested by Borah et al., (1979). An available "Seat Sensor Array" package, originally developed and assembled by the Gulf and Western Applied Science Laboratories for another Air Force program, provided a tool for measuring these contact pressures. This appendix summarizes how this equipment was used to develop a "Drive Law" designed to provide a scaled body-seat contact pressure match. The rather unexpected results obtained during preliminary evaluation of this "Drive Law," and the eventual evolution of the "Drive Laws" used in the formal experiment are also described.

A.2 Apparatus for Measurement of Body-seat Contact Pressures

The "Seat Sensor Array" package includes a seat-pan pad with strain gauge force transducers plus electronics necessary for buffering, balancing, and scaling the transducer output signals. The seat-pan pad consists of an array of six strain gauge load cells (Besco Industries, Series BL101) embedded in a 0.107 inch thick neoprene rubber pad. Figure A-1 portrays the pad

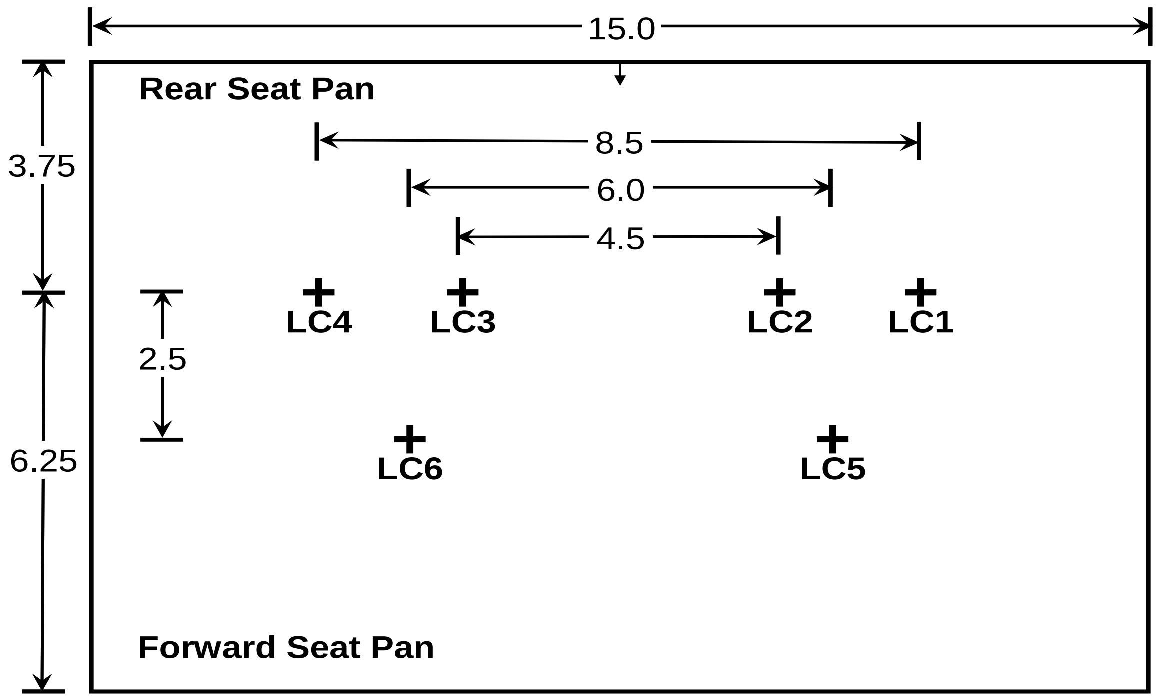

Figure A-1. Seat-pan pad load cell (LC) layout

Each load cell is one inch square and 0.095 inches thick. All dimensions are shown in inches.

dimensions and transducer arrangement. Load cells LC2 and LC3 are placed in the general area of highest expected buttocks-seat contact pressure, i.e., in the region of the ischial tuberosities.

The remaining four transducers are positioned along contours of nearly equal buttocks pressures, according to the buttocks pressure profiles in Gum (1973) and Kron (1975). The load cells are calibrated directly in terms of contact pressure by placing a two inch square aluminum plate faced with 7/16 inch thick, medium density silicone sponge (sponge side down to mimic a “flesh-like” surface) on each load cell, and then placing weights on the aluminum plate. The cells tend to take on a “set” when loaded, i.e., the output voltage changes in response to the initial application of a load, but requires several minutes to return to zero once the load is removed. It was observed, however, that the changes in sensor output voltage about the set state do correctly reflect the actual changes in loading. Therefore, calibration is done in terms of the change in output voltage with a change in applied load, rather than in terms of absolute load. Ten weights, equally spaced over the range of 0.22 to 22 pounds (resulting in 0.055 to 5.5 psi distributed over the aluminum plate) are used. Systematic departures from linearity are indicative of a mismatch between the thickness of the cell and that of the surrounding rubber pad, and are corrected using shims. After calibration, the absolute error obtained over the ten measurements typically averages about 10% for each load cell.

A.3 Development of Body-seat Contact Pressure Measurement Procedures

A methodology for using the seat pad sensors to collect buttocks pressure data was empirically derived using several small subject groups (four to six subjects per group) in studies distributed over some twelve months. Each subject group was balanced for sex and limited to body weights less than 180 pounds (the weight limit recommended by the Applied Science Laboratories due to the fragility of the load cells). Data were initially collected using all six pad sensors. However, the high attrition rate of these extremely frail, ceramic-based load cells soon compelled the reduction of sensors used to two. Subsequently pressure measurements were taken using only LC2 and LC3, the load cell pair at which the greatest sensitivity to buttocks pressure change had been observed during the earlier work.

An investigation was carried out to determine the best placement of the subject with respect to the sensor pad, and of the pad with respect to the seat pan. This investigation also addressed whether it would be better to leave the “tuberosity blocks” in place, or to remove them from the seat. Various combinations of sensor pad placement referenced to the seat pan and referenced to each individual’s tuberosities were tried, both with the “blocks” in place and removed. The combination which provided both good sensitivity and good data repeatability was that wherein the tuberosity blocks were in place and the two load cells were centrally located (in the fore-aft direction) over the blocks. This was the configuration used to collect data for the “Drive Law” development.

In order to obtain the most repeatable data, it has been found best to seat a subject so as to maximize the symmetry of the static readings from the sensor pair before any dynamic data are collected. Mismatches between an individual’s anatomy and the sensor layout, combined with the extreme caution which must be exercised so that the cells are not damaged (subjects cannot slide about on the sensor pad, but must carefully raise off and lower back onto the pad in order to reposition themselves) make this a rather exacting process. Since even with this process it is difficult to precisely reposition a subject from day to day, repeated runs under the same set of conditions have frequently shown pressure differences of 20 to 40%.

As was previously mentioned, the load cells tend to take a “set” under static loading. This set is further confounded with low -requency drift. An early attempt to obtain static buttocks pressure data for RATS cab roll angles in the 0.0 to 5.0 degree range (corresponding to the tilt angle range observed with this task by Levison et al., (1979) in a previous study) was in fact abandoned because the magnitude of the drift swamped the data. Changes in load cell output voltage do correctly reflect actual changes in loading, however, so long as the frequency of these changes is sufficiently above the drift frequency. For this reason the buttocks pressure data used in the “Drive Law” development were collected using forcing functions at frequencies of 0.1 Hz and higher. Sinusoidal forcing functions were considered appropriate since the experimental task involves the steady-state tracking of an input composed of thirteen sinusoids distributed over a limited range of frequencies (0.03 to 5.10 Hz).

A.4 Determination of the Pressure Producing Mechanism in the Dynamic Seat

Buttocks pressure data were collected in the dynamic seat utilizing three of the subjects previously used to develop the pressure measurement procedures. These subjects (one male and two female) were selected on the basis of their availability and the quality and range of data earlier obtained. One female yielded buttocks pressures representative of the higher pressures previously observed; the other female typified the low pressure range, while the male characterized the midrange. Subjects were instructed to sit in an alert posture (as if tracking), and a television broadcast was presented on the monitor in order to maintain their attention on the screen during collection of pressure data.

One aspect of the investigation dealt with the determination of the frequency dependency of the buttocks pressures imparted by the seat. This was explored by sweeping the frequency of the seat roll command signal from 0.1 to 2.0 Hz while maintaining the peak signal amplitude constant. A Brush Strip Chart Recorder was used for data collection. Fifteen sets of frequency-swept data were collected in all, with commanded peak roll spanning the range from 1.2 to 4.7 degrees-peak (corresponding to 1.0 to 4.0 volts-peak). This covered the range of primary interest without placing undue stress either on the subjects or the load cells. Spot checks at lower frequency (0.04 Hz) and at higher amplitude (7 degrees-peak) revealed no deviations from the trends otherwise observed. The only frequency effect observed exhibited a pressure amplitude resonant peak or dip which consistently occurred in the vicinity of 1.5 Hz. The predominant effect observed was amplitude "rolloff," but this was seen to change to blooming in one case where a subject was removed from the seat and immediately reseated—indicating a sensitivity to subject placement. The magnitude of the blooming or "rolloff" ranged from 0.0 to 0.11 psi (averaged 0.016 psi) over the 15 cases observed. There was no correlation between this change in pressure and the magnitude of the pressures obtained at low-frequency, which ranged from 0.13 to 0.48 psi over the 15 cases (the sample correlation coefficient was 0.01). Since the average effect is small and occurs at frequencies above those where the predominant effectiveness of useful motion information was expected to be seen (Shirley (1968) concludes that the effect of useful motion information will be manifest in the vicinity of 0.5 Hz), it was decided that the frequency effect could be neglected. Subsequently buttocks pressure data were collected in the dynamic seat only at 0.5 Hz, a relevant frequency—according to Shirley's findings—which is fortuitously well above the range of load cell drift.

Further data were collected from the three subjects to determine the relationship between seat pan roll amplitude and buttocks pressure. Two complete sets of data were obtained from each subject—each set on a different day. Each data set consisted of pressure readings, taken in randomized order, for commanded sinusoidal seat pan roll motion ranging from 0.6 to 7.0 degrees peak. Data were again collected using a Brush Strip Chart Recorder; a sample record is shown in Fig. A-2.

An available BMD stepwise regression program (Dixon, 1973) was used to obtain a zero-intercept, least-squares fit to the data. Peak buttocks pressure was the dependent variable; peak seat pan roll angle was the independent variable. This yielded the following relationship.

$$\mathit{Buttock\ Pressure}\ (\text{psi}) = (0.081) \bullet \mathit{Seat\ Roll}\ (\text{degrees}) \quad \text{......................................(A-1)}$$

The coefficient of simple determination for this fit was 0.94.

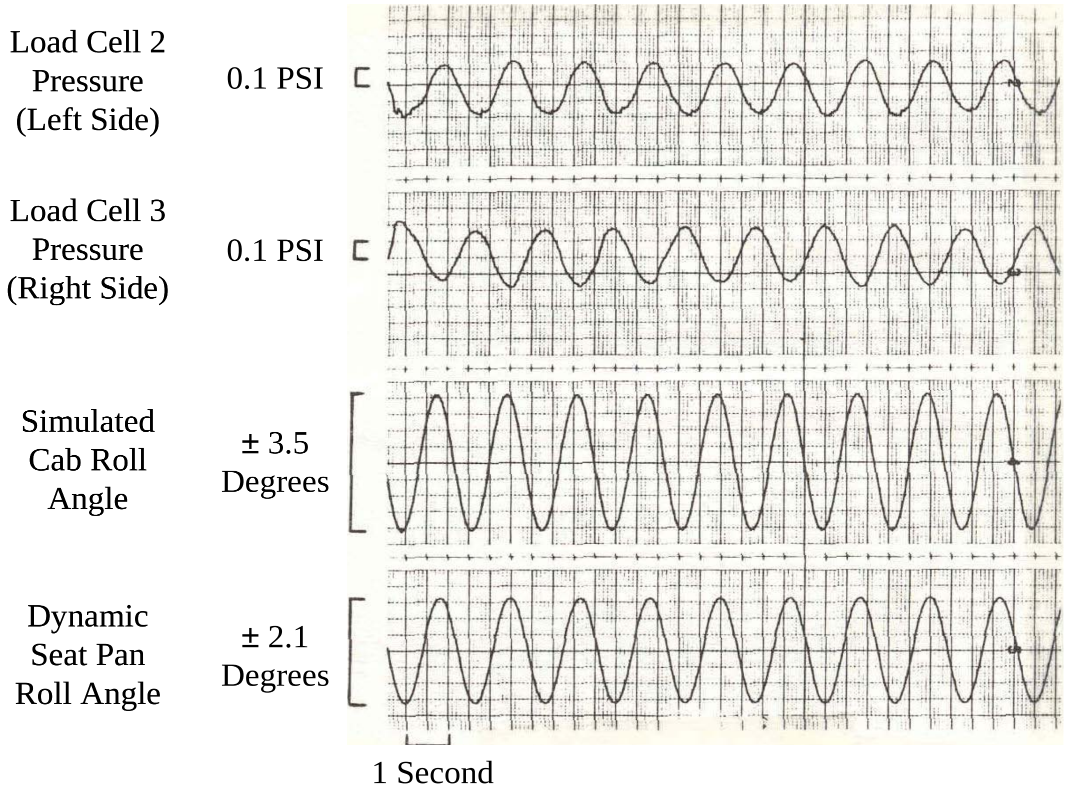

Figure A-2. Representative buttocks pressure measurements taken in the dynamic seat The measured buttocks pressures are shown along with the analog simulation of the cab's roll angle and the dynamic seat pan roll angle. Positive roll is defined as "right wing" down.

A.5 Determination of the Pressure Producing Mechanism in the Criterion Device

Before collecting buttocks pressure data in the criterion device, i.e., the RATS, a rough mathematical analysis was carried out to gain some insight regarding the principal pressure producing forces which would be operating on the buttocks in the vicinity of load cells LC2 and LC3. The following encapsulates this analysis.

The motion of a particle fixed relative to a rotating coordinate system (the RATS coordinate system) as observed from inertially fixed space can be obtained from the relationship for vector time differentiation across coordinate systems in relative rotational motion (Goldstein, 1965;

p 133). The resultant specific force vector acting on this particle, SF, is the vector sum of the specific force required to oppose the gravity force vector, G, superimposed upon the specific force needed to impart rotational motion. That is,

$$\underline{SF} = -\underline{G} + (\underline{\omega'} \times \underline{r}) + \underline{\omega} \times (\underline{\omega} \times \underline{r}) \quad \text{(A-2)}$$

where $\underline{\omega}$ and $\underline{\omega'}$ are the angular velocity and acceleration vectors, respectively. Equ.(A-2) is the specific force vector as observed in inertially fixed space. This vector can be geometrically projected onto the RATS coordinate system.

Assume the conventional right-handed aircraft coordinate system (x-axis positive forward, y-axis positive toward the right wing, and z-axis positive downward). Since the only cab motion is roll about the RATS x-axis, the only non-zero components of $\underline{\omega}$ and $\underline{\omega'}$ in the RATS coordinate system are p and p', the RATS roll rate and roll acceleration respectively. Carrying out the geometric projection of –G onto the RATS axes and combining with the cross product terms carried out in RATS coordinates yields:

$$SF_y = -\sin(R) - p^2\left(\frac{y}{386}\right) - p'\left(\frac{z}{386}\right)$$
$$SF_z = -\cos(R) - p^2\left(\frac{z}{386}\right) + p'\left(\frac{y}{386}\right) \quad \text{(A-3)}$$

where y and z specify the location of the particle relative to the RATS coordinate system origin in inches, p is the angular rate in rad/s, p' is the angular acceleration in rad/s/s, R is the cab roll angle, and the specific force components are in g-units (1 g-unit = 386 inches/s/s).

Load cells LC2 and LC3 are sensitive to changes in the z-component of the specific force vector. The lateral distance to load cell LC3 is 2.25 inches (with a corresponding offset to LC2 along the negative y-axis). The roll axis is through the seat pan; therefore the z offset is zero. Substituting these values into Equ.(A-3) and solving for the z-component yields:

$$SF_z = -\cos(R) + \left(\frac{p'}{172}\right) \quad \text{(A-4)}$$

From Equ.(A-4) it is seen that both roll angle (tilt) and roll acceleration contribute to changes in buttocks pressures. Tilt further affects buttocks pressures since there is insufficient lateral support to impart the full lateral specific force component to the subject as required by Equ.(A-3). This requires an additional moment be imparted to the subject's buttocks via the seat pan. This moment is in phase with the SF_y tilt component (opposite the phase of the roll angle). Further, because the center-of-mass is above the roll axis (i.e., in the negative z direction), and because of the phase inversion which exists between the roll angle and roll acceleration in sinusoidal motion, this tilt effect is in phase with the acceleration effect. Equ.(A-3) also has a velocity dependent term in the lateral component of specific force. However, any lateral offset to a subject's torso center-of-mass should be small with respect to the vertical offset. Further, the squared angular velocity term involves the square of the angular excursion amplitude (which is small—roll excursions rarely exceed 0.2 rad), whereas the tilt and acceleration terms scale linearly with excursion amplitude (for small roll angles). It was therefore anticipated that any contribution due to angular velocity would be negligible. This expectation was later borne out by the data.

Angular excursion histograms and summaries of angular velocities and accelerations from tracking data from an earlier study employing the same task variables (Levison et al., 1979) were reviewed in order to determine the appropriate range of the independent variables for collection of RATS pressure data. Reasonable operational upper limits for peak angular excursion, velocity, and acceleration were found to be 6.0 degrees, 20.0 degrees/s, and 100.0 degrees/s/s respectively. In light of the foregoing analysis, it was decided to place the emphasis on manipulating excursion and acceleration, so long as the velocity range was appropriately covered. To do this, it was decided to vary the peak roll angle in five steps from 1.0 to 6.0 degrees. At each excursion step, data were taken at several frequencies in order to provide data over the acceleration range of interest. This also resulted in data over the velocity range of interest.

The three subjects used previously in the dynamic seat were again used in the RATS. The RATS cab was driven sinusoidally. Data were collected for thirty-five excursion-frequency combinations with each subject. The sequence in which data were collected was randomized for each subject. A BAFCO Frequency Response Analyzer (Model 916) was used to monitor the gain and phase relationships of the load cell outputs relative to the RATS model position. The time history data were also stored on magnetic tape for subsequent digital analysis, wherein a Digital Fourier Transform (DFT) was employed to estimate the amplitude and phase of each recorded signal.

Gain and phase of the load cell outputs relative to the actual cab position were obtained via the DFT. There was no observable phase angle dependence on frequency. The output of LC3 was in phase with the cab roll angle; the LC2 output was phase inverted relative to roll. A BMD stepwise regression (Dixon, 1973) used to fit the data yielded the following regression surface.

$$\text{Buttocks Pressure} = -0.064\,(\text{Roll}) + 0.0042\,(\text{Acceleration}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\text{A-5})$$

where Buttocks Pressure is in psi, RATS Roll is in degrees, and Acceleration is in degrees/s/s; peak values for each variable were used in fitting the data. The negative sign accounts for the phase inversion of roll angle relative to acceleration; recall that their pressure producing effects are in phase with one another.

The coefficient of multiple determination for this fit was 0.86. Earlier work had shown that a better fit was possible by including a Roll X Acceleration interaction term. This was not done however because it would lead to a non-linear “Drive Law” and the introduction of sum and difference frequencies not linearly correlated to the tracking task’s disturbance input. The inclusion of a velocity term was also investigated, but found not useful in explaining the data.

A.6 Development and Evaluation of a Buttocks-pressure Drive Law—The Initial Pilot Study

A seat cuing “Drive Law” designed to provide a scaled body-seat pressure match was obtained by equating the buttocks pressure fits in Equ.(A-1) and Equ.(A-5), and solving for the seat roll angle in terms of the RATS cab roll and acceleration. This resulted in:

$$\text{Seat Roll} = K\,[\,-0.79\,(\text{RATS Roll}) + 0.052\,(\text{RATS Acceleration})\,] \;\ldots\ldots\ldots\ldots\ldots(\text{A-6})$$

where the simulated RATS (i.e., analog model) roll and acceleration values, in degrees and degrees/s/s, would be used in practice (see Chapter 2). The gain factor, K, is introduced to allow for scaling. Two values of K were used in evaluating this "Drive Law." The higher value of 0.40 (40% of RATS pressures) was selected on the basis of preventing the seat pan from striking the travel limits excessively, particularly with a naïve tracker. The lower value of 0.25 (25% of RATS pressures) was selected as a value low enough that a naïve tracker would not find the seat activity discomforting, yet would receive what was judged to be adequate cuing.

A pilot study was undertaken to evaluate the effectiveness of the above "Drive Law." The disturbance regulation task to be used in the formal experiment was employed. Human performance for a group of six subjects (five male and one female) was compared for the following two conditions:

(1) The dynamic seat was driven in accordance with Equ.(A-6). The gain was set to 0.40 for three subjects and to 0.25 for the other three.

(2) The dynamic seat was static.

All subjects were alternated between the two conditions and completed nine sessions (each session consisting of four 3-minute runs) under each condition. Fig. A-3 shows average tracking performance as a function of the two conditions over the first nine sessions. A consistent improvement in performance (lower tracking error) is seen with the Buttocks-pressure "Drive Law."

A Split-plot Factorial ANOVA—appropriate for the mixed analysis involving a between group factor (GAIN) and a within group factor ("SESSIONS")—was carried out to determine whether Buttocks-pressure "Drive Law" gain resulted in any significant performance differences. The results, presented in Table A–1, show no significant gain effect ($F(1,4)=0.02$). The significant main effect of "SESSIONS" simply indicates that the improvement in Buttocks-pressure tracking performance with practice, which is observable in Fig. A-3, is statistically significant. Since performance scores at the two levels of gain were indistinguishable, these were pooled so that scores with Buttocks-pressure "Drive Law" cuing could be compared to scores with the seat static. A Randomized Block Factorial ANOVA—appropriate where subjects underwent all levels of both factors—was then conducted to test for differences due to seat cuing (Table A-2). A significant main effect of seat cuing was found ($F(1,5)=15.3$). Again, the significant main effect of "SESSIONS" simply indicates that subjects were improving with practice.

Despite the statistical significance found for "seat cuing" differences, the result was not considered operationally significant in light of the tracking performance differences expected. Past data for the same experimental task (Levison et al., 1979) indicate that tracking errors in the presence of good motion cuing should approach a value of three degrees. Clearly this was not achieved with the Buttocks-pressure "Drive Law."

"Sessions" 10 through 12 were carried out for Condition (1) alone to determine whether any improvement in performance might be seen with additional practice. No significant change was observed.

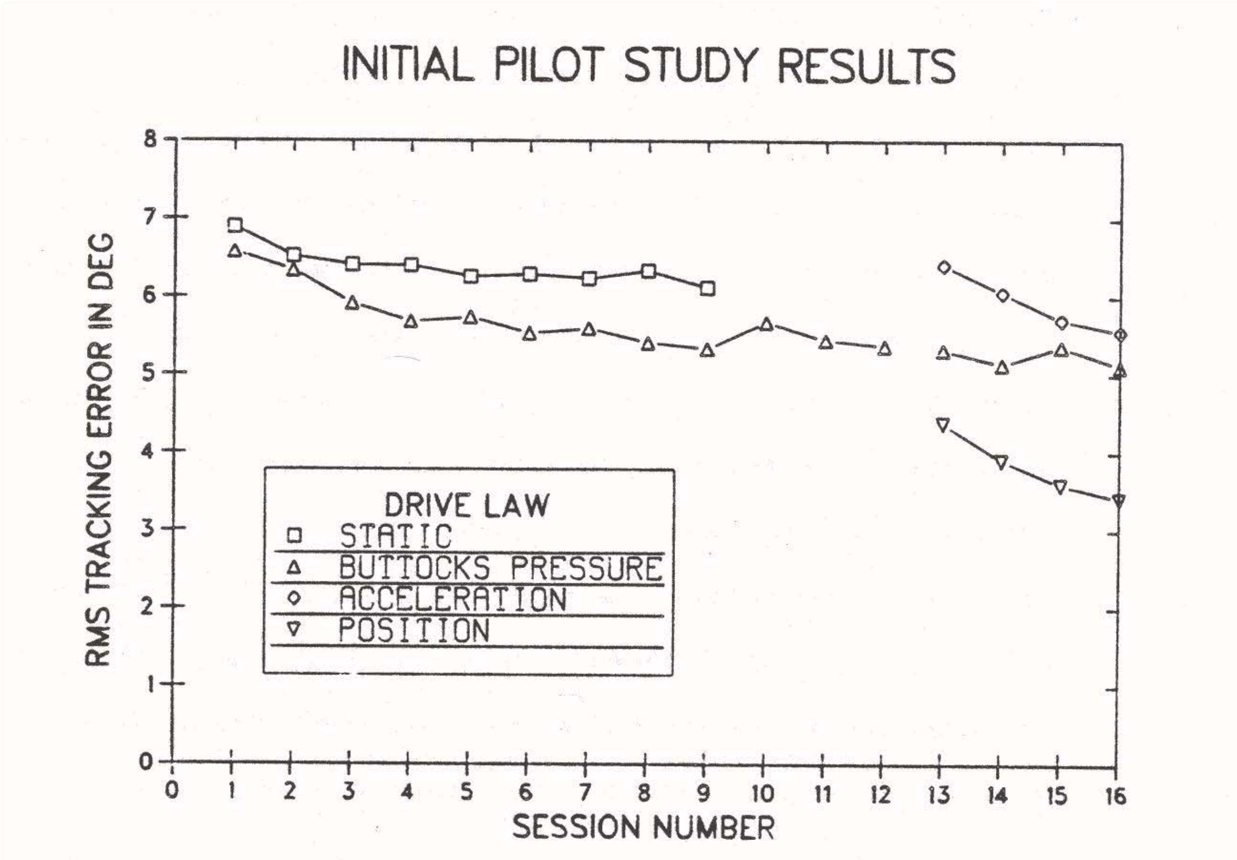

Figure A-3. Average tracking performance in the dynamic seat during the first pilot study
Session averages are shown to reduce clutter. Six subjects were alternated between a Buttocks-pressure Drive Law and a static seat for sessions 1 to 9, then continued with just Buttocks-pressure for sessions 10 to 12. Two subjects were retained as controls while the other four subjects were provided pure position and pure acceleration cues in a counterbalanced sequence during sessions 13 to 16. The Buttocks-pressure, Acceleration, and POSITION "Drive Laws" were respectively:

$$Seat\ Roll = K\left[-0.79 \times Model\ Roll + 0.052 \times Model\ Acceleration\right]$$
$$Seat\ Roll = K\left[0.052 \times Model\ Acceleration\right]$$
$$Seat\ Roll = 0.40\left[-0.79 \times Model\ Roll\right]$$

where "model" refers to the analog simulation of the whole-body motion device, roll is in degrees, and acceleration in degrees/s/s. The scale factor K was set to 0.40 for half the subjects, and to 0.25 for the other half.

Table A–1. Tracking performance compared at two gain levels of Buttocks-pressure "Drive Law"

This is a Type SPF-2.9 Split Plot Design. Factor A has two levels of GAIN (0.25 and 0.40). Factor B has nine levels of "SESSIONS." Subjects (blocks) within each group received all levels of B, but only one level of A. The dependent variable is the session average rms tracking error for sessions 1 through 9 (Fig. A-3).

ANALYSIS OF VARIANCE TABLE FOR TYPE SPF-2.9 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
A	0.05	1	0.05	0.02	NS		.00
Subject within Group	12.72	4	3.18				
B	8.01	8	1.00	10.39	**	**	.29
AB	1.19	8	0.15	1.54	NS	NS	.02
B X Subject w. Group	3.08	32	0.10				
TOTAL	25.05	53					

** $p < 0.05$ $F(.05;1,4) = 7.71$
NS = Not Significant $F(.05;8,32) = 2.24$

Table A–2. Tracking performance with seat driven by Buttocks-pressure "Drive Law" vs. performance with seat static

This is a Type RBF-29 Randomized Block Factorial Design. Factor A has two levels of SEAT CUING (Buttocks-pressure "Drive Law" versus Seat Static). Factor B has nine levels of "SESSIONS." Repeated measures were taken on all subjects for nine sessions at each level of A. The dependent variable is the session average rms tracking error for sessions 1 through 9 (Fig. A-3).

ANALYSIS OF VARIANCE TABLE FOR TYPE RBF-29 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
BLOCKS	25.07	5	5.02	36.70	**		.47
RESIDUAL	11.62	85	1.19				
A	9.93	1	9.93	15.33	**	**	.16
A X BLOCKS	3.24	5	0.65				
B	8.91	8	1.11	7.45	**	**	.13
B X BLOCKS	5.98	40	0.15				
AB	1.43	8	0.18	2.98	**	NS	.01
AB X BLOCKS	2.40	40	0.06				
TOTAL	56.96	107					

** $p < 0.05$ $F(.05;1,5) = 6.61$ $F(.05;5,85) = 2.32$
NS = Not Significant $F(.05;8,40) = 2.18$

It was decided next to see whether the acceleration or excursion component of the "Drive Law" might be masking useful information provided by the other. A pure position "Drive Law" was derived from Equ.(A-6) by setting the acceleration coefficient to zero. Similarly, a pure acceleration "Drive Law" was obtained by setting the excursion coefficient to zero. Two of the original six subjects were maintained as controls, while the other four were provided pure position and pure acceleration cuing in a counterbalanced sequence. As is seen in Fig. A–3 (sessions 13 through 16), subjects provided position information immediately improved and began approaching tracking performance levels expected with full-body motion. Subjects provided acceleration information regressed, and did somewhat more poorly than they were doing with the pressure matching "Drive Law." With these results, it was decided to drop consideration of the pure acceleration "Drive Law" and to pursue the pure position "Drive Law" instead. It was also decided to look at the potential utility of a velocity "Drive Law" on the basis of both cue substitution (under the assumption that, with seat cuing, the subject is being deprived of useful angular velocity information normally picked up via the semicircular canals (Milsum, 1966)) and completeness (in terms of investigating the effects of first derivative information as well as zero and second order information).

The Position Drive Law tested was derived from Equ.(A-6) by setting the coefficient for acceleration to zero and selecting the higher gain (K=0.40) in order to maximize the cues which practiced trackers would receive at small roll angles. The resulting Position "Drive Law" was:

$$\text{Seat Roll (degrees)} = \pm\, 0.32 \bullet \text{Model Roll (degrees)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(A-7)}$$

where the "model" refers to the analog simulation of the RATS cab. Since no attempt was now being made to produce an analog of Buttocks-pressure, it was not clear that the sign obtained from Equ.(A-6) was appropriate. For this reason, the algebraic sign associated with the seat drive was included as a dependent variable in the continuation of the study.

A Velocity "Drive Law" was derived by patching model velocity into the roll ADC and changing the scaling. This resulted in:

$$\text{Seat Roll (degrees)} = \pm\, 0.23 \bullet \text{Model Velocity (degrees/s)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(A-8)}$$

The velocity scaling was initially set by selecting a gain which was judged to produce a reasonable level of cuing. The gain was then adjusted by a small amount so that the seat roll could accommodate three times the overall rms velocity obtained during the previous twelve Buttocks-pressure Drive Law sessions. This was equivalent to adjusting the scale factor to accommodate three standard deviations of the observed velocity (which would account for 99.7% of all velocity commands, under the assumption of a zero-mean normal distribution).

The pilot study was continued to compare these three “Drive Laws” (Buttocks-pressure, Position, and Velocity) using the same group of six subjects. The two controls remained with the Buttocks-pressure “Drive Law.” The remaining four subjects were distributed between the Position and Velocity “Drive Laws,” balanced according to tracking performance during the earlier Buttocks-pressure tracking sessions; opposite “Drive Law” signs were randomly assigned to one subject in each of these latter two groups. Each subject was trained for eight sessions (32 runs), allowing all to reach apparent asymptotic performance. All subjects were then transitioned to the full-body motion environment where tracking continued for another five sessions (20 runs), at which time they all appeared to have again reached asymptotic performance. Fig. A–4 through A–6 show tracking performance versus runs, both during training in the seat and following transition to the whole-body motion environment.

In Fig. A–4 through A–6 it is seen that the position and velocity groups’ asymptotic tracking errors during training (say runs 25-32, which cover the last two sessions of training—at one session per day) more closely resembled their asymptotic performance in the motion environment (runs 45-52) than was the case for the Buttocks-pressure group. As seen in the figures, the Buttocks-pressure “Drive Law” pair smoothly transitioned to the full motion environment, virtually replicating their last training scores on the first full motion run. The data further show, however, that a substantial amount of post-transition learning is occurring for the Buttocks-pressure group relative to what is seen with the other two groups—despite the discontinuities observed in the position and velocity groups’ tracking performance at transition.

One can also compare asymptotic control behavior in training to that with whole-body motion in terms of similarities in the Human Operator Describing Functions. This provides further insight into the usefulness of the motion information. From Shirley’s (1968) conclusions regarding roll motion cuing effects on the Human Operator Describing Function, one would expect that good motion cues would result in increased phase lead above 3 rad/s, and higher operator gain than would be obtained with a static environment.

Asymptotic describing function data are available for the six subjects used in this pilot study <u>while tracking in the static environment</u> (corresponding to static sessions 8 and 9 in Fig. A–3), <u>while training with their respective "Drive Laws"</u> (corresponding to runs 25-32 in Fig. A–4 through A–6), and <u>while tracking with whole-body motion</u> (runs 45-52 in Fig. A–4 through A–6). These are shown for the Buttocks-pressure group, the Position group, and the Velocity group in Fig. A–7 through A–15. These figures show that under static conditions little high-frequency phase lead is introduced and low-frequency operator gain is low relative to non-static conditions (Fig. A–7, A–10, and A–13). The Buttocks-pressure "Drive Law" subjects show a marginal increase in phase lead and gain relative to the static condition (Fig. A–8), but this improvement is small when compared to control behavior in the full motion environment (Fig. A–9). The Position "Drive Law" (Fig. A–11) appears to be more effective than the Buttocks-pressure "Drive Law," although the gain and phase lead with position seat cuing is somewhat less than with full motion (Fig. A–12). In contrast, the effectiveness of the Velocity "Drive Law" (Fig. A–14) was a surprise. It was seen that this subject pair was able to inject <u>more</u> high-frequency phase lead with seat cuing than with full-body motion and adopted comparable gain levels under both conditions (Fig. A–15).

The differences seen in the describing functions are also reflected in the tracking error shown in Fig. A–4 through A–6. Where subjects are better able to inject phase lead, tracking error tends to be lower. In fact close inspection of Fig. A–6 discloses that the Velocity "Drive Law" pair obtained lower tracking errors with seat cues than with full motion. On the other hand, the Position "Drive Law" pair did a little worse with seat cues—albeit considerably better than the Buttocks-pressure "Drive Law" pair.

The data collected during this initial pilot study generally indicate the superior effectiveness of both the Position and Velocity "Drive Law" over the Buttocks-pressure "Drive Law." Although the velocity pair outperformed the position pair during seat training, it was not clear from this limited amount of data that either of these two "Drive Laws" was necessarily better than the other in this application. It was therefore decided to continue investigating both the Velocity and Position "Drive Laws," but to drop any further consideration of the Buttocks-pressure "Drive Law."

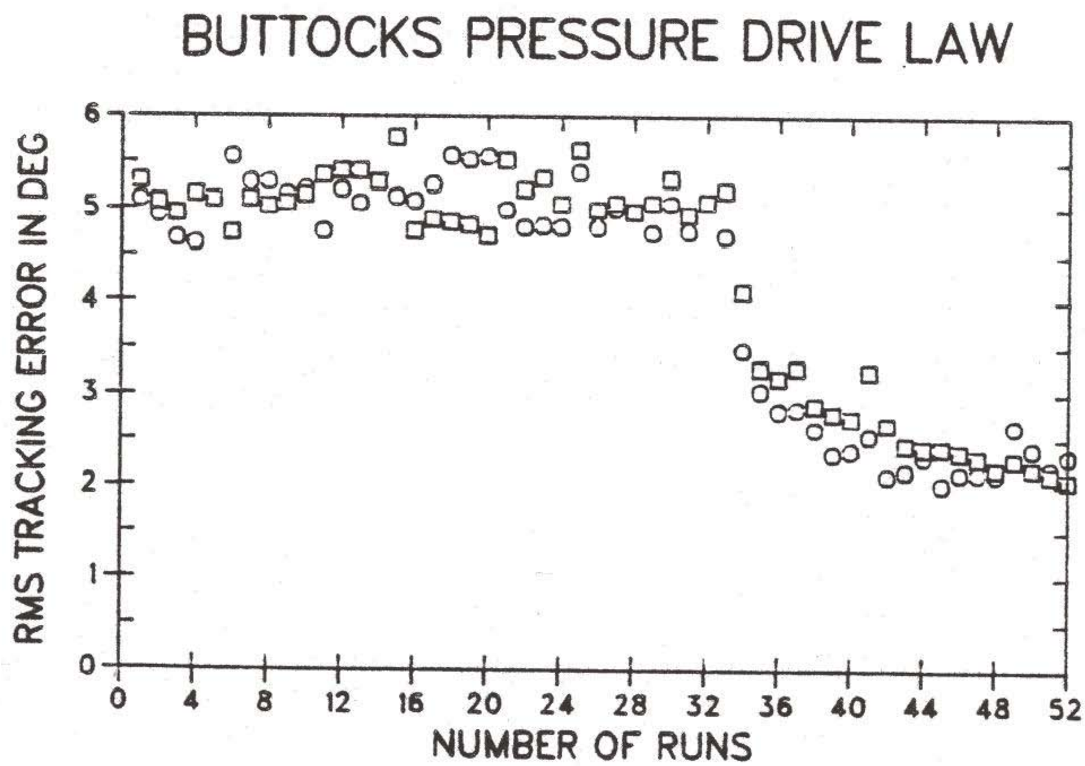

Figure A-4. Tracking performance with the <u>Buttocks-pressure "Drive Law"</u> during the first pilot study

The first pilot study compared the effectiveness of the Position and Velocity "Drive Laws" to that of the Buttocks-pressure "Drive Law." Tracking scores are shown for <u>Subject 014 (squares)</u> and for <u>Subject 015 (circles)</u>, who were respectively trained with the following Buttocks-pressure "Drive Laws":

$$Seat\ Roll = 0.40\left[-0.79 \times Model\ Roll + 0.052 \times Model\ Acceleration\right]$$

$$Seat\ Roll = 0.25\left[-0.79 \times Model\ Roll + 0.052 \times Model\ Acceleration\right]$$

where "model" refers to the analog simulation of the whole-body motion device, roll is in degrees, and acceleration in degrees/s/s. Runs 1 through 32 were training runs in the seat. Runs 33 through 52 show subsequent tracking in the whole-body motion environment.

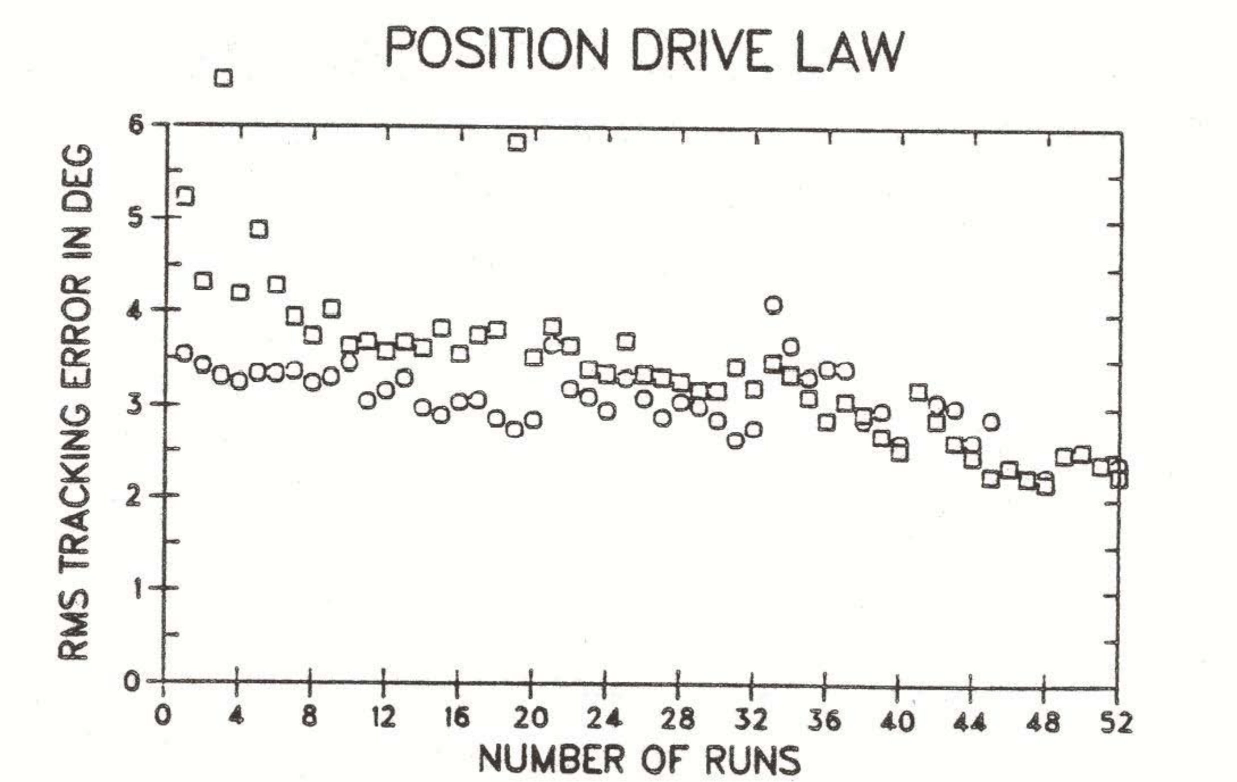

Figure A-5. Tracking performance with the Position "Drive Law" during the first pilot study

The first pilot study compared the effectiveness of the Position and Velocity "Drive Laws" to that of the Buttocks-pressure "Drive Law." Tracking scores are shown for Subject 012 (squares) and for Subject 013 (circles), who were respectively trained with the following Position "Drive Laws":

$$\textit{Seat Roll}\ \text{(degrees)} = +0.32 \times \textit{Model Roll}\ \text{(degrees)}$$

$$\textit{Seat Roll}\ \text{(degrees)} = -0.32 \times \textit{Model Roll}\ \text{(degrees)}$$

where "model" refers to the analog simulation of the whole-body motion device. Runs 1 through 32 were training runs in the seat. Runs 33 through 52 show subsequent tracking in the whole-body motion environment.

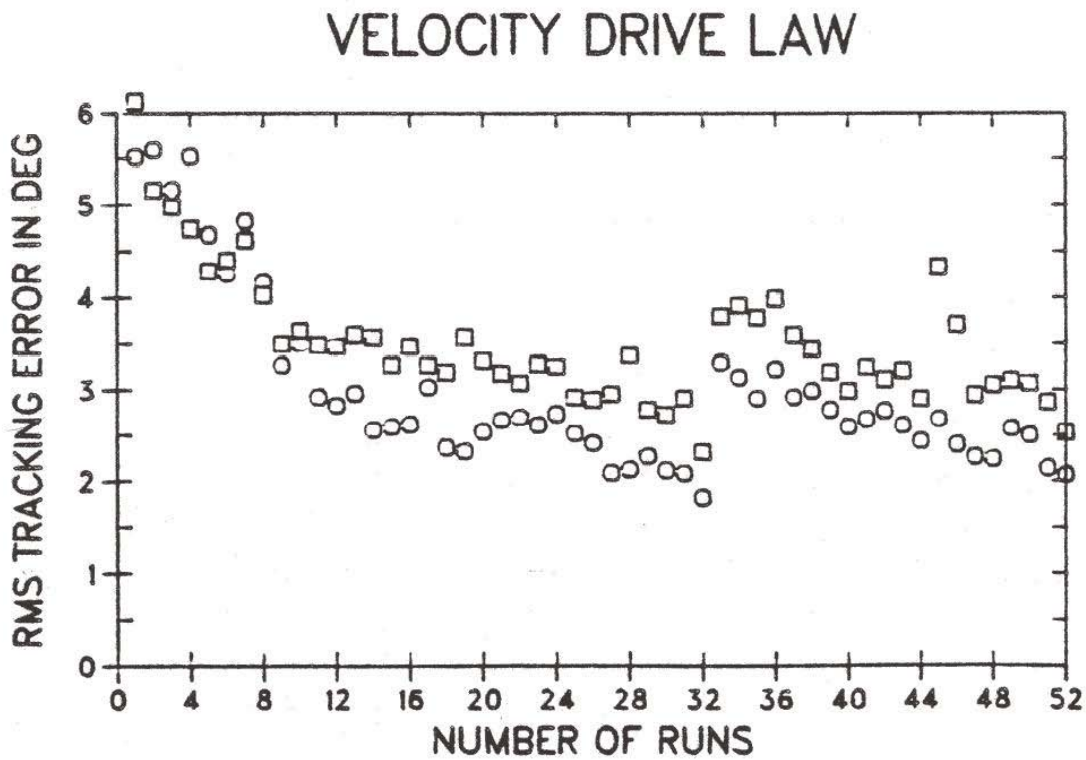

Figure A-6. Tracking performance with the Velocity "Drive Law" during the first pilot study

The first pilot study compared the effectiveness of the Position and Velocity "Drive Laws" to that of the Buttocks-pressure "Drive Law." Tracking scores are shown for Subject 010 (squares) and for Subject 011 (circles), who were respectively trained with the following Velocity "Drive Laws":

$$\textit{Seat Roll}\ \text{(degrees)} = +0.23 \times \textit{Model Roll Velocity}\ \text{(degrees/s)}$$

$$\textit{Seat Roll}\ \text{(degrees)} = -0.23 \times \textit{Model Roll Velocity}\ \text{(degrees/s)}$$

where "model" refers to the analog simulation of the whole-body motion device. Runs 1 through 32 were training runs in the seat. Runs 33 through 52 show subsequent tracking in the whole-body motion environment.

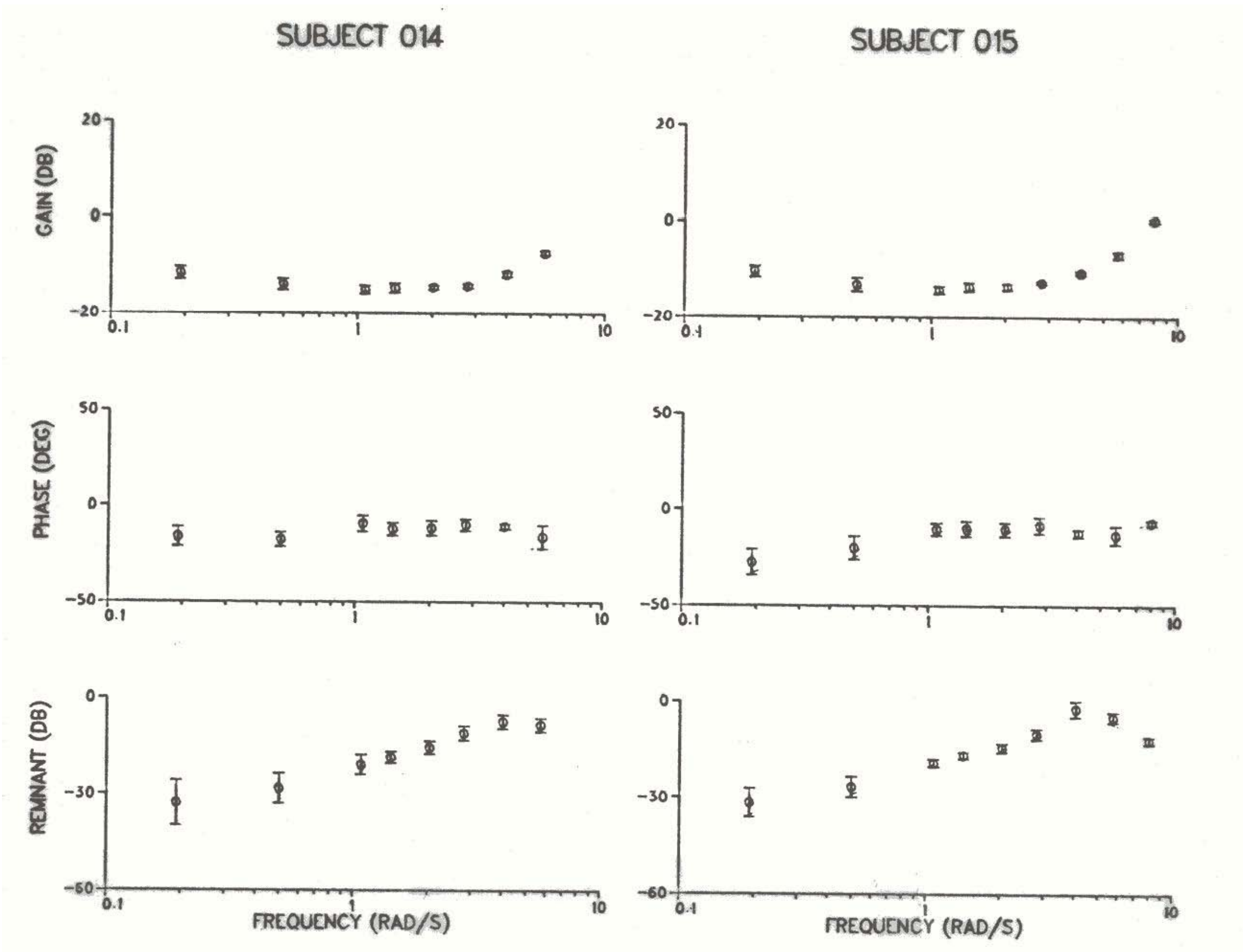

Figure A-7. Asymptotic HODF obtained from the Buttocks-pressure subject pair during <u>static training</u>

These data reflect average control behavior during the last eight training runs under static conditions. Mean values, plus/minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

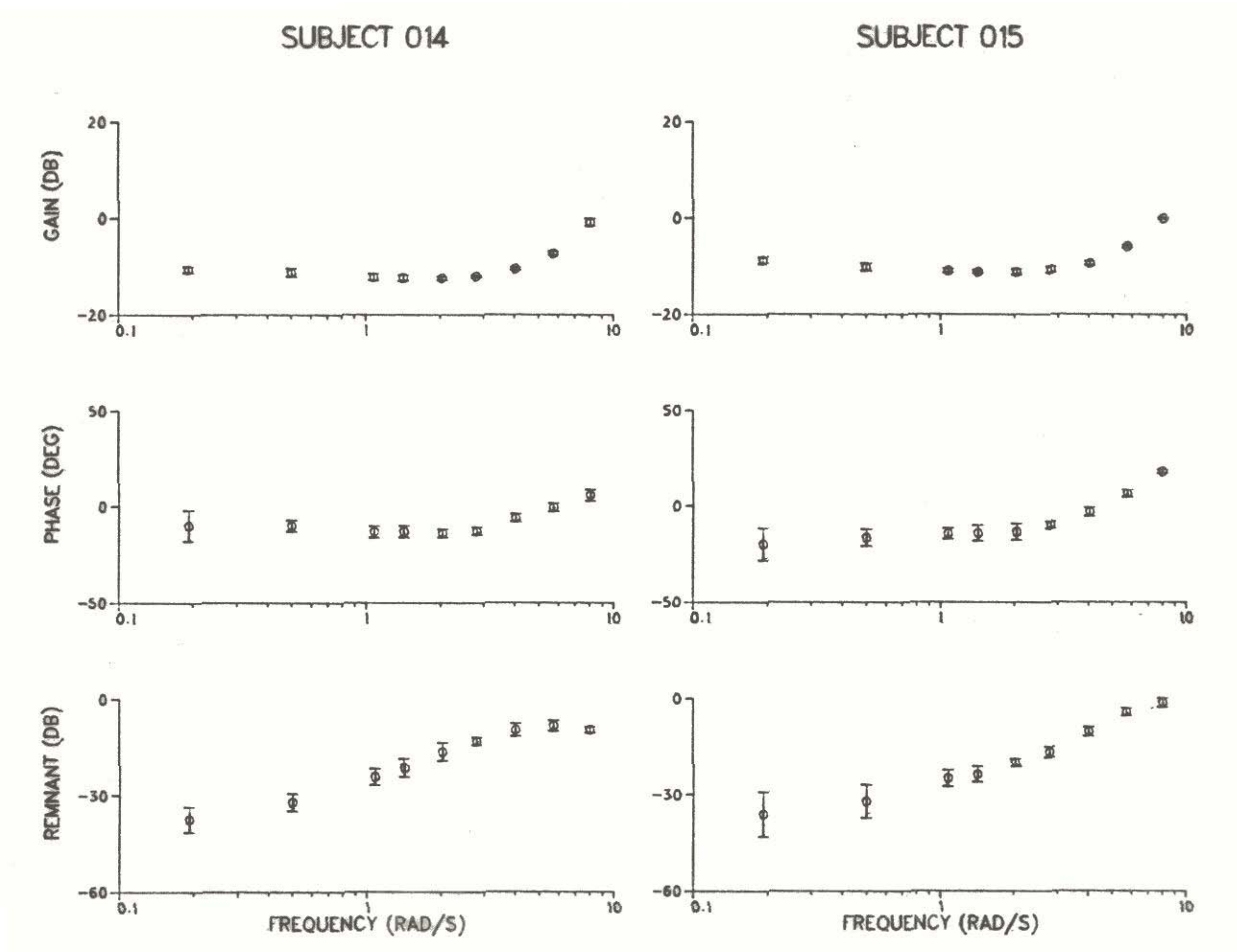

Figure A-8. Asymptotic HODF obtained from the Buttocks-pressure subject pair during <u>Buttocks-pressure "Drive Law" training</u>

The drive laws for Subject 014 and Subject 015, respectively, were:

$$Seat\ Roll = 0.40\left[-0.79 \times Model\ Roll + 0.052 \times Model\ Acceleration\right]$$

$$Seat\ Roll = 0.25\left[-0.79 \times Model\ Roll + 0.052 \times Model\ Acceleration\right]$$

where "model" refers to the analog simulation of the whole-body motion device, roll is in degrees, and acceleration in degrees/s/s. These data reflect average control behavior during the last eight training runs. Mean values, plus/minus one standard deviation, are shown.

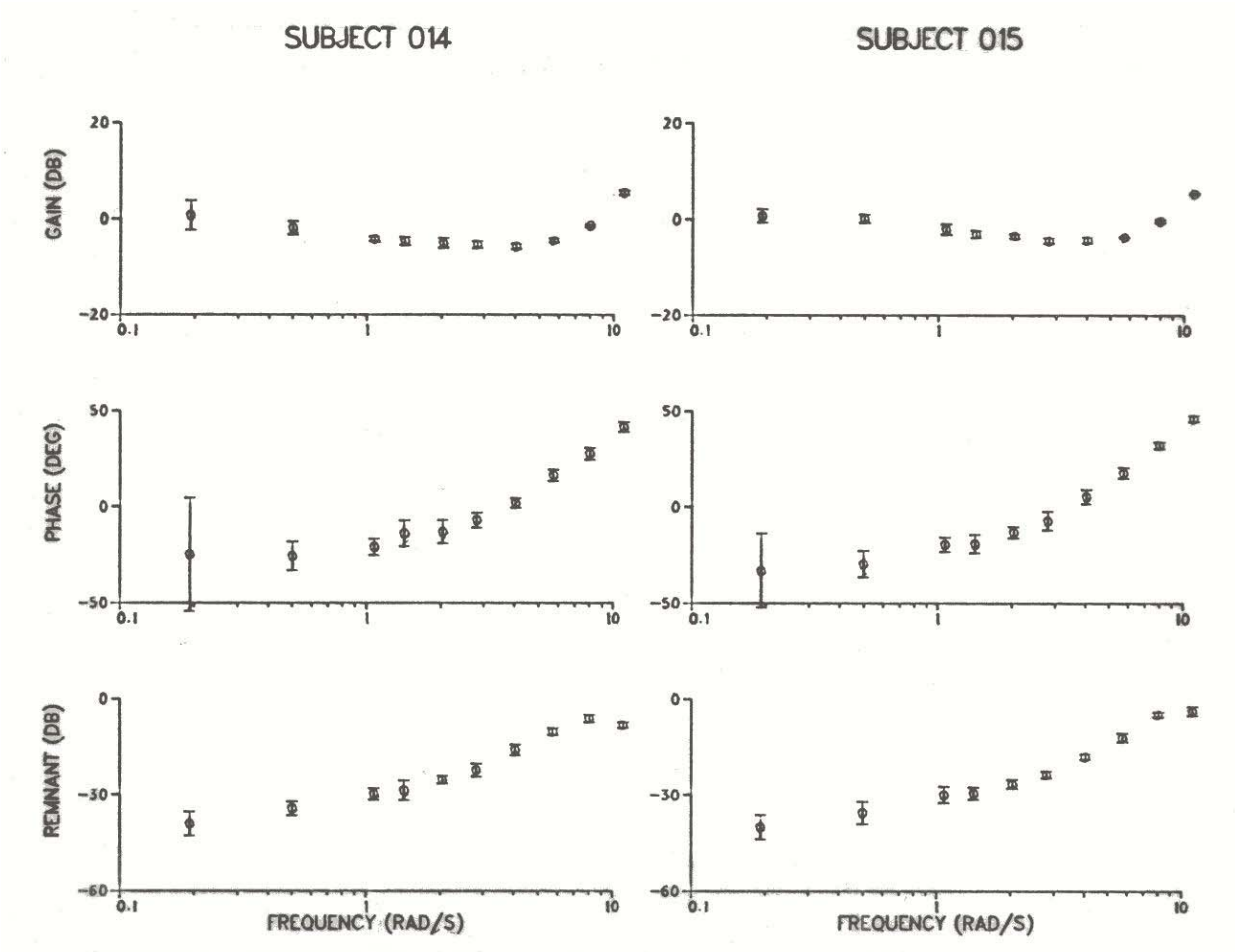

Figure A-9. Asymptotic HODF obtained from the Buttocks-pressure subject pair with <u>whole-body motion</u>

These data reflect average control behavior during the last eight runs in the full-motion device. Mean values, plus/minus one standard deviation, are shown.

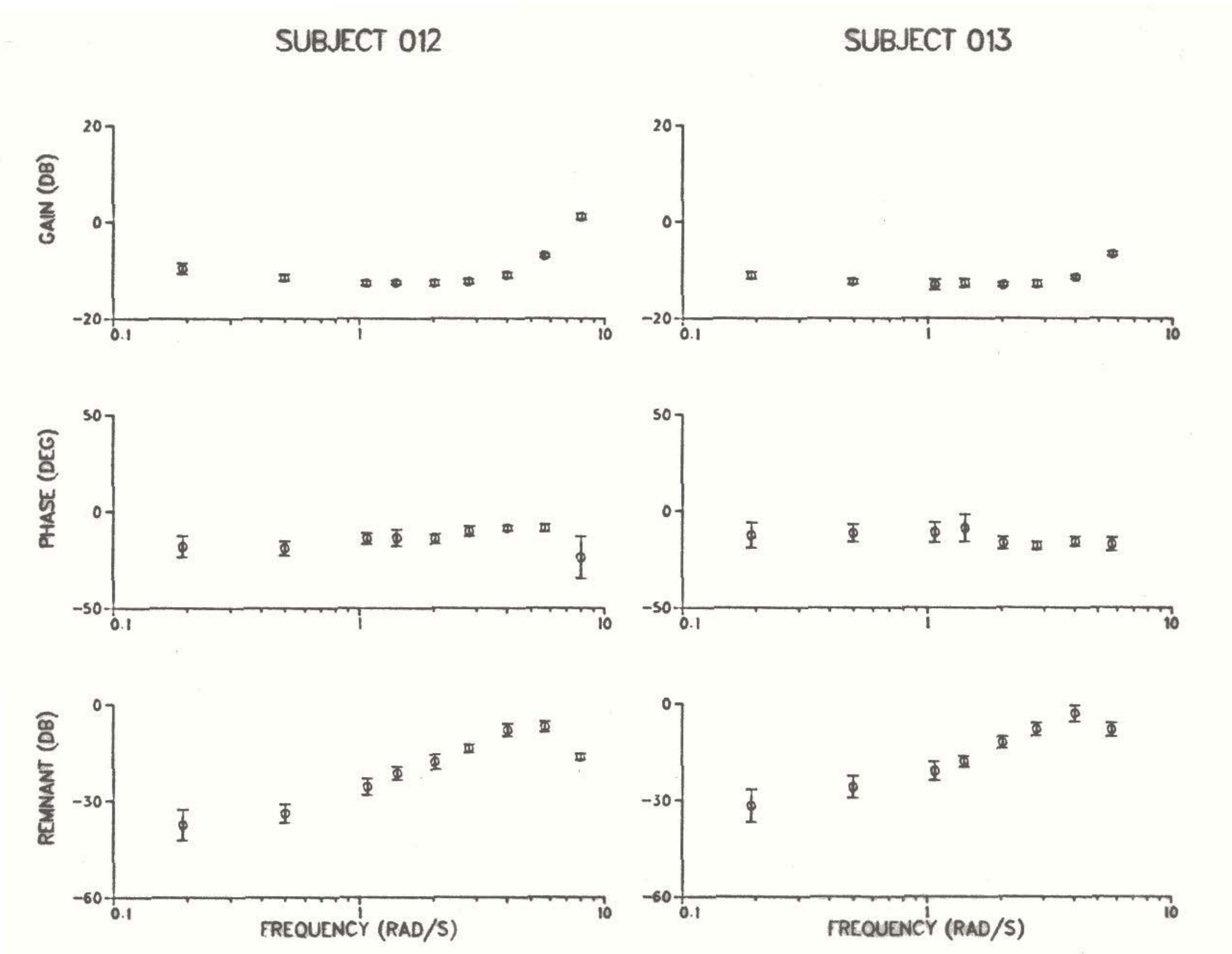

Figure A-10. Asymptotic HODF obtained from the Position "Drive Law" subject pair during <u>static training</u>

These data reflect average control behavior during the last eight training runs under static conditions. Mean values, plus/minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

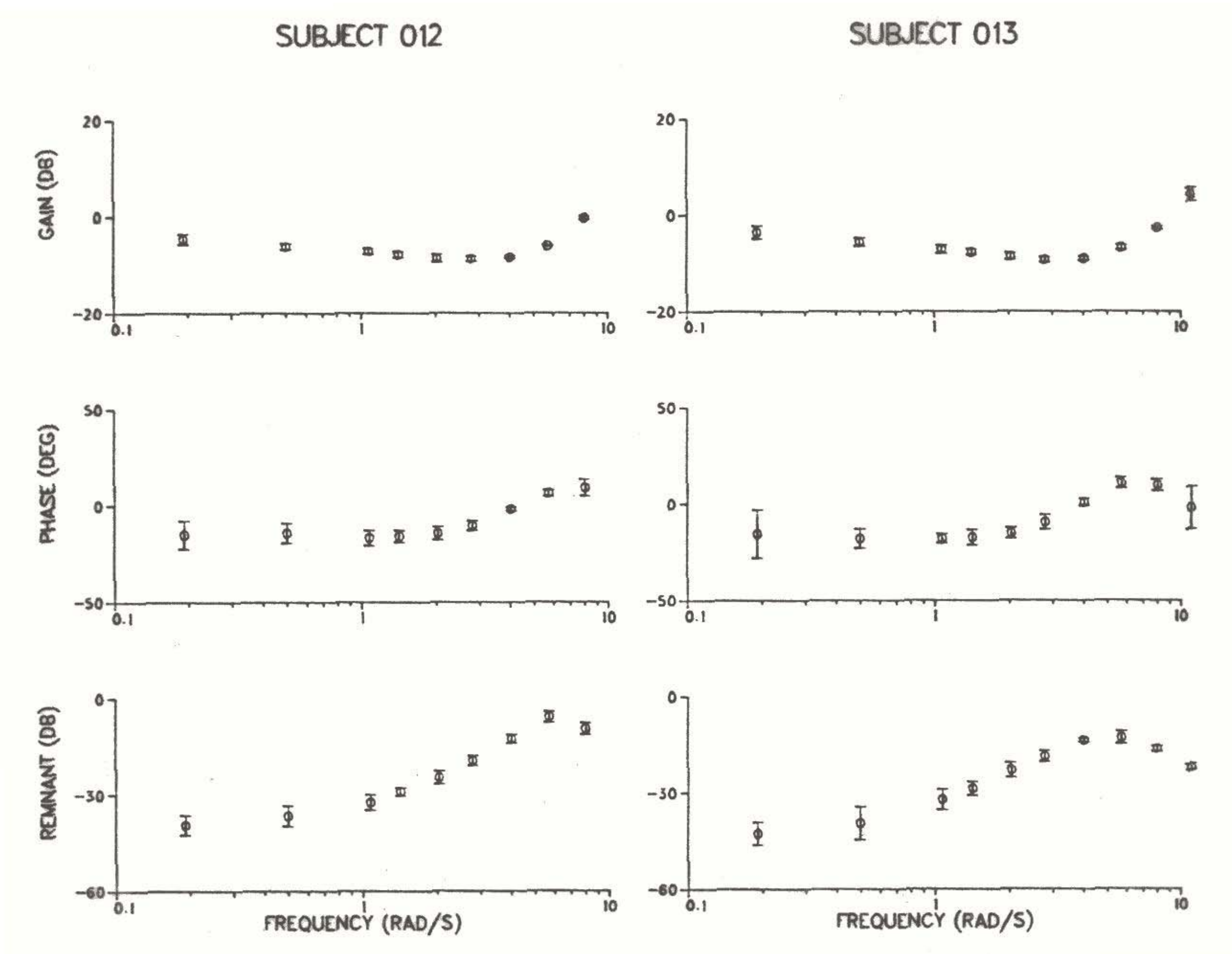

Figure A-11. Asymptotic HODF obtained from the Position "Drive Law" subject pair during <u>Position "Drive Law" training</u>

The drive laws for Subject 012 and Subject 013, respectively, were:

Seat Roll (degrees) = +0.32 × *Model Roll* (degrees)

Seat Roll (degrees) = −0.32 × *Model Roll* (degrees)

where "model" refers to the analog simulation of the whole-body motion device, and the algebraic sign indicates the phase relationship. These data reflect average control behavior during the last eight training runs. Mean values, plus/minus one standard deviation, are shown.

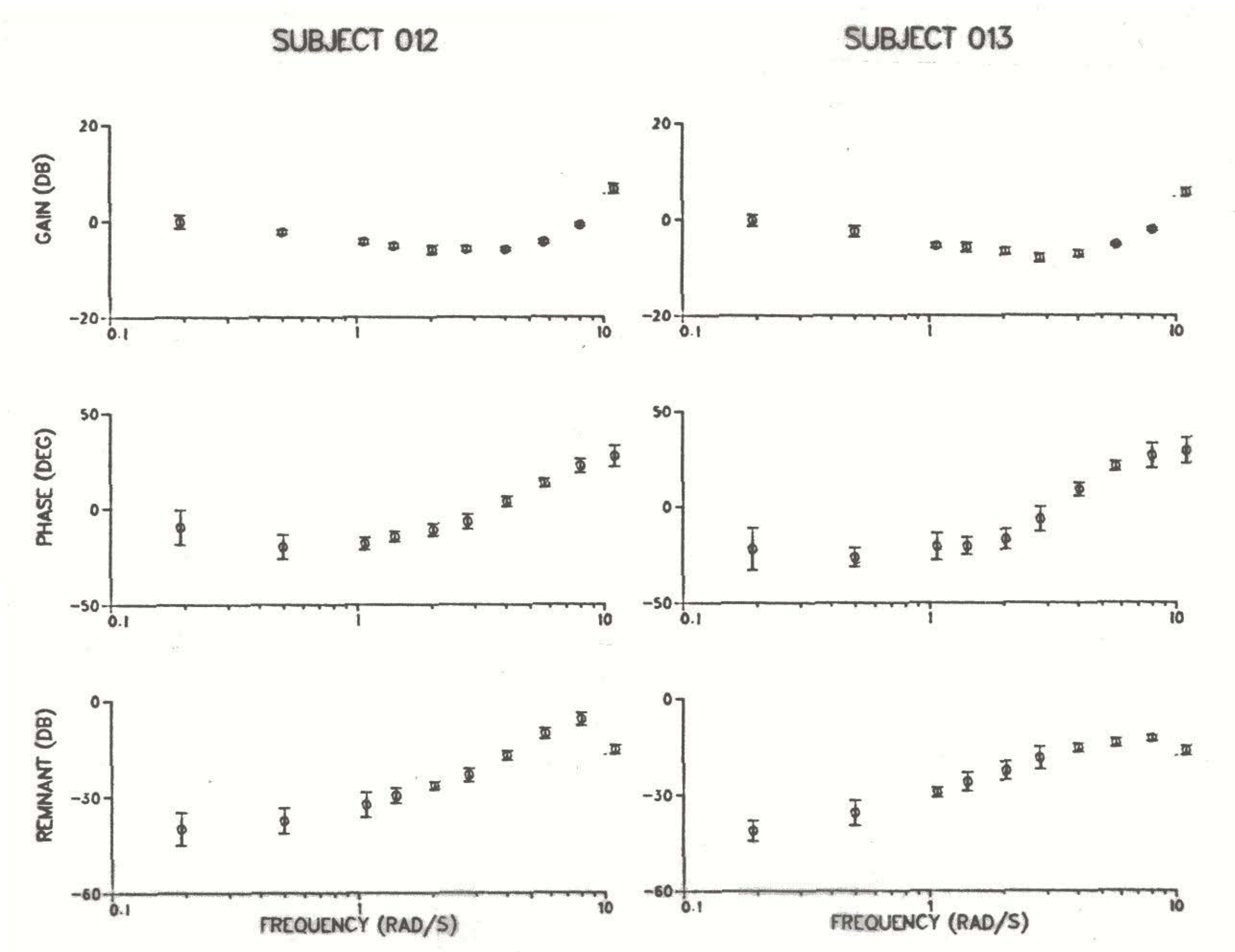

Figure A-12. Asymptotic HODF obtained from the Position "Drive Law" subject pair with <u>whole-body motion</u>

These data reflect average control behavior during the last eight runs in the full-motion device. Mean values, plus/minus one standard deviation, are shown.

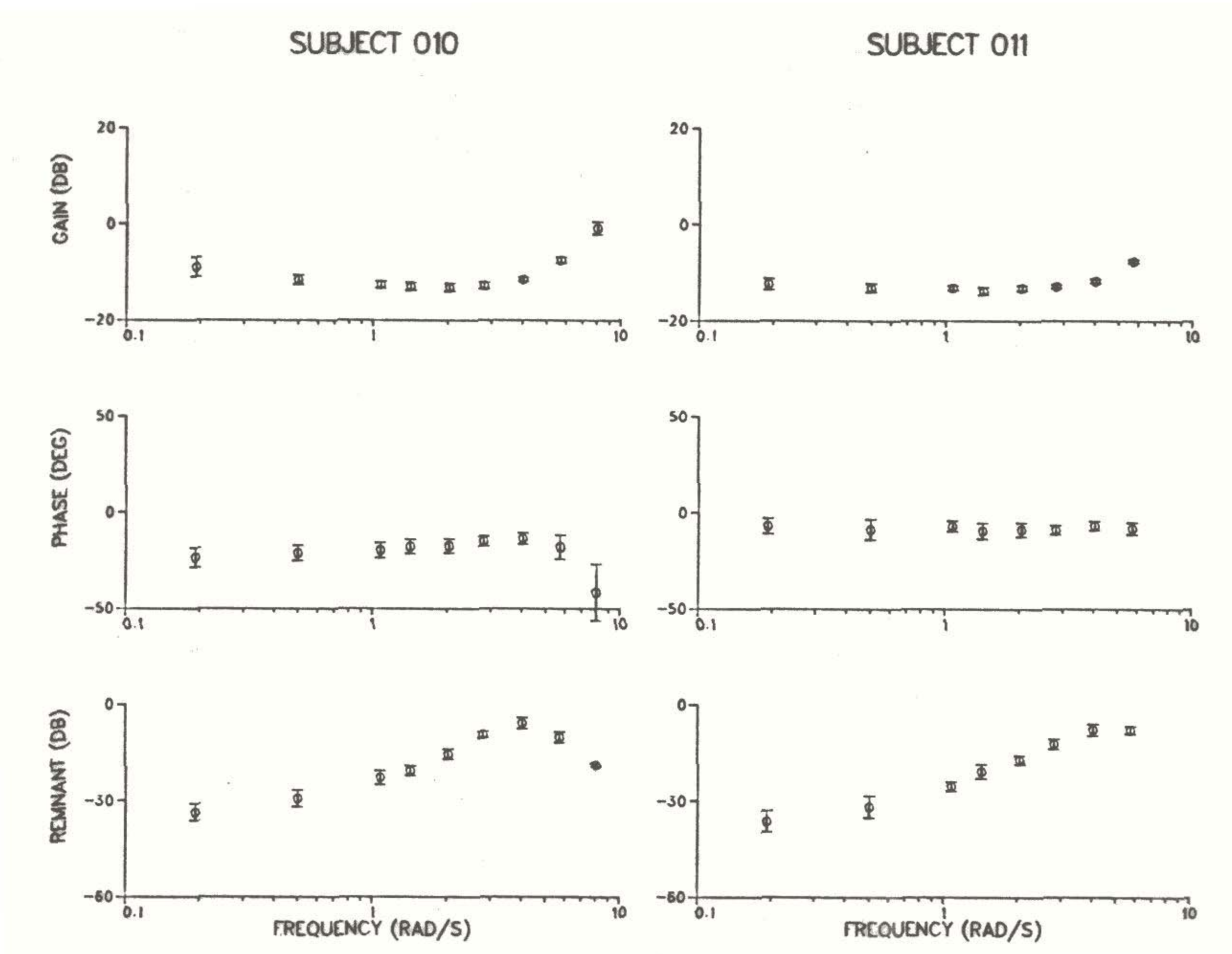

Figure A-13. Asymptotic HODF obtained from the Velocity "Drive Law" subject pair during <u>static training</u>

These data reflect average control behavior during the last eight training runs under static conditions. Mean values, plus/minus one standard deviation, are shown. The GAIN and PHASE curves characterize that portion of the operators' response linearly correlated with the input; the measured closed-loop control-action REMNANT accounts for the remaining portion of the operator response. Zero db represents 1 lb control force per degree roll error for operator GAIN, and (1 lb control force)^2 per rad/s for REMNANT.

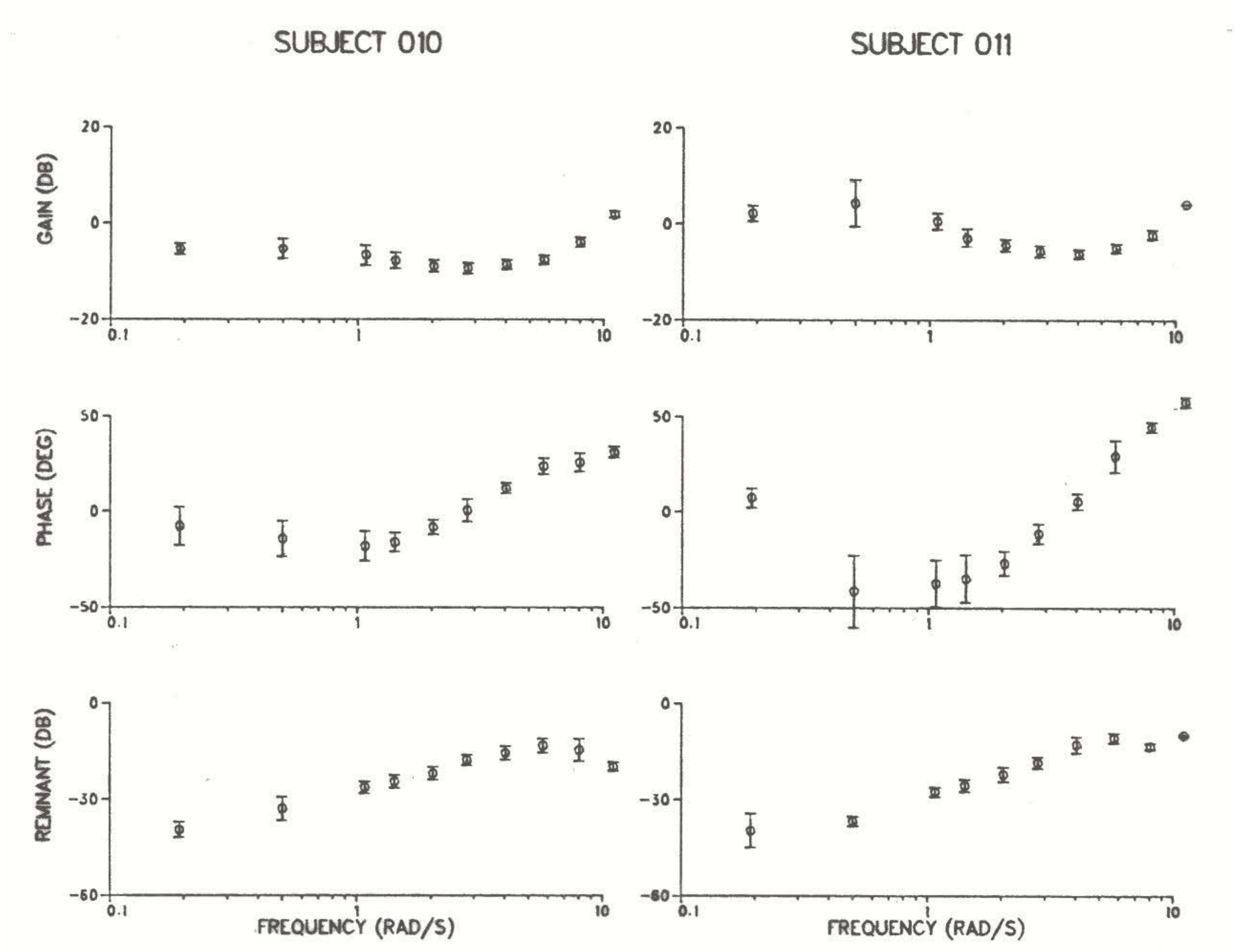

Figure A-14. Asymptotic HODF obtained from the Velocity "Drive Law" subject pair during <u>Velocity "Drive Law" training</u>

The drive laws for Subject 010 and Subject 011, respectively, were:

$$Seat\ Roll \text{ (degrees)} = +0.23 \times Model\ Roll\ Velocity \text{ (degrees/s)}$$

$$Seat\ Roll \text{ (degrees)} = -0.23 \times Model\ Roll\ Velocity \text{ (degrees/s)}$$

where "model" refers to the analog simulation of the whole-body motion device, and the algebraic sign indicates the phase relationship. These data reflect average control behavior during the last eight training runs. Mean values, plus/minus one standard deviation, are shown.

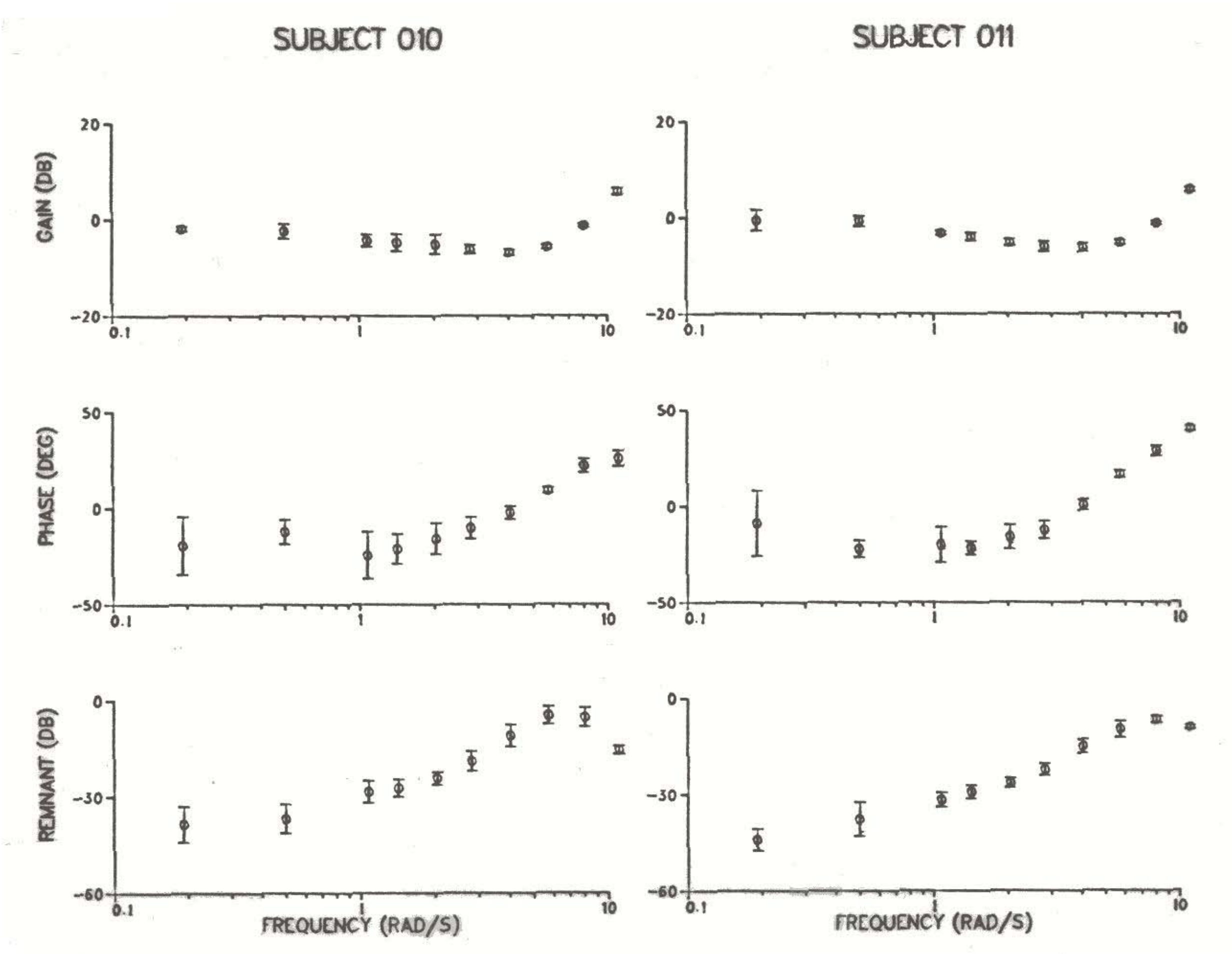

Figure A-15. Asymptotic HODF obtained from the Velocity "Drive Law" subject pair with <u>whole-body motion</u>

These data reflect average control behavior during the last eight runs in the full-motion device. Mean values, plus/minus one standard deviation, are shown.

A.7 Evaluation of the Effectiveness of Lap Belt and Radial Element Cuing

The dynamic seat included two active radial wing elements located at the lower outboard corners of the backrest, as well as an active lap belt. These elements could all be driven independently of the seat pan. One reason for the inclusion of these elements in the dynamic seat was to provide for the enhancement of roll-axis cuing via the lateral scrubbing action of the lap belt and the lower back pressure changes produced by the radial elements. The lap belt and radial elements were used through the initial pilot study. It was decided to run a quick evaluation regarding the influence of these elements on tracking performance at the end of the first pilot study because, subjectively, these elements did not appear to be providing any significant cuing benefit when they were used. Available subjects from the first pilot study were used, and tracking data were collected over two sessions (8 runs). Subjects tracked with the drive laws under which they had previously trained. Repeated measures were taken on all subjects for both treatment conditions. The data were subjected to a Randomized Block Factorial ANOVA (Kirk, 1968), the results of which are presented in Table A–3. As seen in the table, only the main effect of “blocks” is significant ($F(4,28)=186$). Since different “Drive Laws” were used with different subjects (i.e., “blocks”), this result is hardly surprising—especially considering the large differences already seen as a function of “Drive Law.” These results confirmed the suspicions that the lap belt and radial elements were not significantly influencing tracking performance. In light of this, and in the interest of parsimony, the radial elements were deactivated and the lap belt was allowed to float with the seat pan (i.e., no lap belt cues were provided) for the remainder of the study.

Table A–3. Tracking performance with and without lap belt & radial element cuing

This is a Type RBF-24 Randomized Block Factorial Design. Factor A has two levels of LAP BELT and RADIAL ELEMENT cues (on and off). Factor B has four levels of RUNS. Repeated measures were taken on all subjects for four runs at each level of A. The dependent variable was the rms tracking error tabulated below.

RMS TRACKING ERROR SCORES

	A1 = ELEMENTS ON				A2 = ELEMENTS OFF			
	B1	B2	B3	B4	B1	B2	B3	B4
SUBJECT 010	2.75	2.69	2.46	2.44	2.94	2.71	2.55	2.61
SUBJECT 011	2.62	2.45	2.49	2.21	2.72	2.31	1.88	1.83
SUBJECT 012	3.44	3.02	3.17	2.95	3.48	3.25	3.45	3.35
SUBJECT 014	5.09	6.15	5.02	5.21	5.42	5.14	4.96	4.98
SUBJECT 015	5.91	5.92	6.10	6.00	5.10	5.28	5.03	5.18

ANALYSIS OF VARIANCE TABLE FOR TYPE RBF-24 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
BLOCKS	72.32	4	18.08	185.70	**		.95
RESIDUAL	2.73	28	0.10				
A	0.38	1	0.38	1.10	NS	NS	.00
A X BLOCKS	1.40	4	0.35				
B	0.53	3	0.18	2.89	NS	NS	.00
B X BLOCKS	0.74	12	0.06				
AB	0.12	3	0.04	0.80	NS	NS	.00
AB X BLOCKS	0.59	12	0.05				
TOTAL	76.08	39					

** $p < 0.05$ $F(.05;1,4) = 7.71$ $F(.05;3,12) = 3.49$

NS = Not Significant $F(.05;4,28) = 2.71$

A.8 Evaluation of a Position "Drive Law" and a Velocity "Drive Law"—The Second Pilot Study

A second pilot study was undertaken to continue evaluation of the Position and Velocity "Drive Laws" defined in Equ.(A-7) and (A-8), respectively. A group of eight naïve male subjects underwent the pretest described in Chapter 3; they were then given 14 training sessions in the dynamic seat, followed by transition to the RATS. Subjects were assigned to one of the following four training conditions on the basis of matching average pretest scores across groups:

(1) Position "Drive Law" with the seat roll angle in phase with model (i.e., analog simulation of the RATS) roll angle.

(2) Position "Drive Law" with the seat roll angle phase inverted relative to model roll angle.

(3) Velocity "Drive Law" with the seat roll angle in phase with model roll velocity.

(4) Velocity "Drive Law" with the seat roll angle phase inverted relative to model roll velocity.

One objective of this study was to see whether the trends observed in the initial pilot study held for a larger subject population. Another objective was to collect more data upon which to base a decision regarding the appropriate algebraic sign for the "Drive Laws."

Tracking performance during the 14 training sessions and the 4 post-transition sessions is shown for the four two-subject groups in Fig. A–16. Fig. A–17 through A–20 show the asymptotic Human Operator Describing Functions, averaged across the two subjects within each group and across the last eight runs (two sessions) during seat training and during tracking in the whole-body motion environment.

The data taken during the second pilot study generally showed the same trends evident during the first. It was encouraging to see the trends holding for larger groups, but there was still no clear indication regarding the most appropriate algebraic sign to be assigned to each "Drive Law." The most prominent effect of sign was that subjects using the phase-inverted "Drive Laws" tracked better during training—but transferred worse—than their in-phase trained counterparts. Since better performance during training did not necessarily mean that the subject was being better trained to cope with the full motion environment, tracking performance during training was not considered the most appropriate criterion for selection of the algebraic sign.[8] It was decided to consider tracking similarities both at transfer to the motion environment and at asymptote in arriving at a final judgment regarding the appropriate sign. Estimates for the mean and standard deviation were computed for each group's tracking error, crossover frequency, phase margin, and low-frequency (1 rad/s) gain during the last dynamic seat training run, first full motion run, and final full motion run. A point scheme was devised which reflected how closely the last training run's scores matched the first and last full motion runs' scores—thus providing a combined training transfer and asymptotic performance metric. The rating criteria and results are summarized in Table A–4.

First consider the Position "Drive Law." The ratings in Table A–4 show that there was a stronger similarity between the asymptotic training and motion scores for the phase-inverted than for the in-phase Position "Drive Law." This can also be seen by comparing the asymptotic Human Operator Describing Functions (Fig. A–11, A–12, A–17, and A–18). Unfortunately similarities at transfer suffer dramatically with the phase-inverted "Drive Law." In fact, the tracking error training transfer characteristic evident in Fig. A–5 and A–16 was also seen for crossover frequency, phase margin, and gain; that is, in each instance the phase-inverted position subject did better than his in-phase counterpart during training, but fared worse at transfer. The combined training transfer and asymptotic performance rating in Table A–4 favors selection of the in-phase Position "Drive Law," and that is the "Drive Law" selected for use in the formal experiment.

The in-phase Velocity "Drive Law" came out with higher ratings in Table A–4. In this case similarities at transfer and at asymptote both favor the in-phase "Drive Law," as does an overall

[8] An explanation for the tracking performance differences seen with the different signs is that the seat motion biomechanically coupled back to the control stick in a direction which reduces error if the seat roll is phase inverted. Thus biomechanical coupling from the seat to the control stick aided the phase-inverted drive law subjects, while it slightly increased the task difficulty for the in-phase drive law subjects.

comparison of the Human Operator Describing Functions (Fig. A–14, A–15, A–19, and A–20). The in-phase Velocity "Drive Law" was therefore selected for the formal experiment.

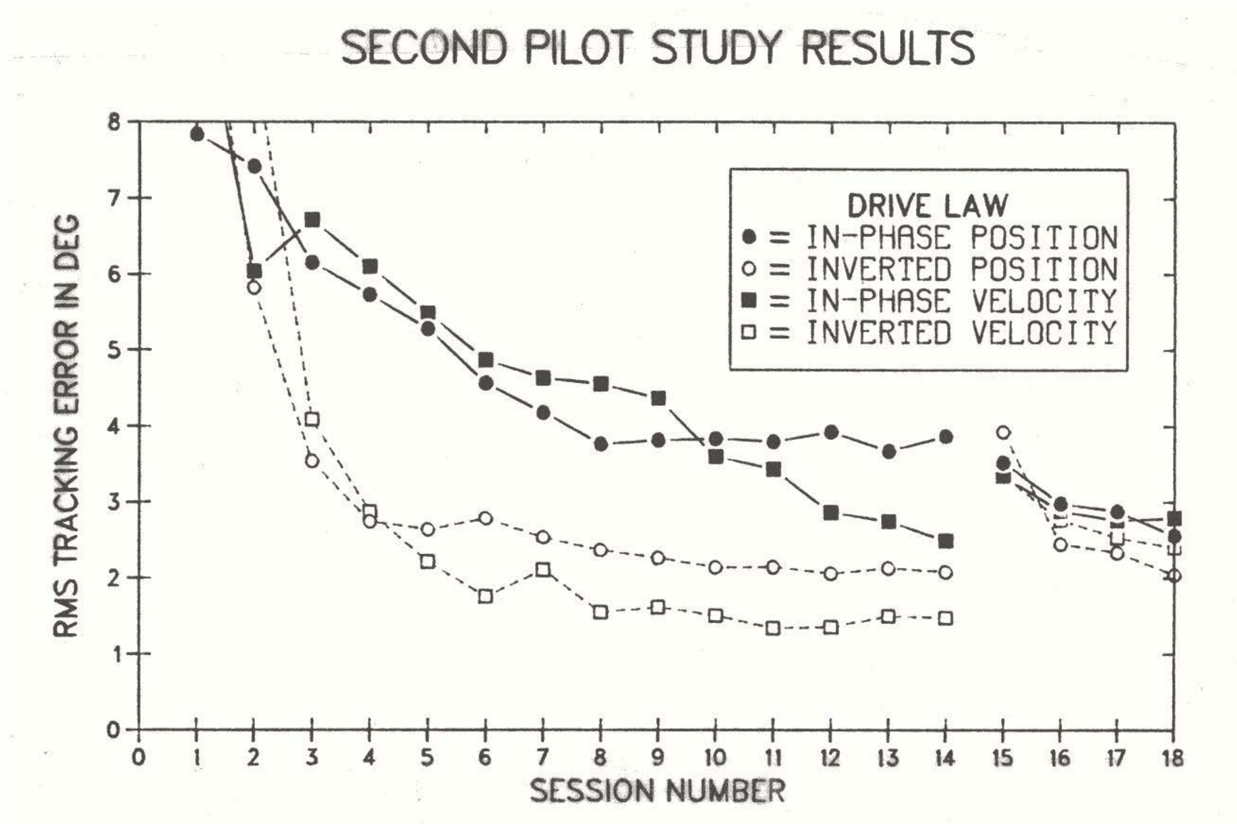

Figure A-16. Average tracking performance during the second pilot study

The effectiveness of the Position and Velocity "Drive Laws" was further investigated. Session averages for each two-subject group are shown. Eight naïve subjects were assigned to one of four "Drive Laws" for training. The <u>Position</u> and <u>Velocity "Drive Laws"</u> were respectively:

$$\textit{Seat Roll}\ (\text{degrees}) = +0.32 \times \textit{Model Roll}\ (\text{degrees})$$
$$\textit{Seat Roll}\ (\text{degrees}) = -0.32 \times \textit{Model Roll}\ (\text{degrees})$$

$$\textit{Seat Roll}\ (\text{degrees}) = +0.23 \times \textit{Model Roll Velocity}\ (\text{degrees/s})$$
$$\textit{Seat Roll}\ (\text{degrees}) = -0.23 \times \textit{Model Roll Velocity}\ (\text{degrees/s})$$

where "model" refers to the analog simulation of the whole-body motion device. A positive algebraic sign corresponds to seat roll being in phase with the model parameter; a negative algebraic sign corresponds to phase inversion. Sessions 1 through 14 were training sessions in the seat. Sessions 15 through 18 show subsequent tracking performance in the whole-body motion environment.

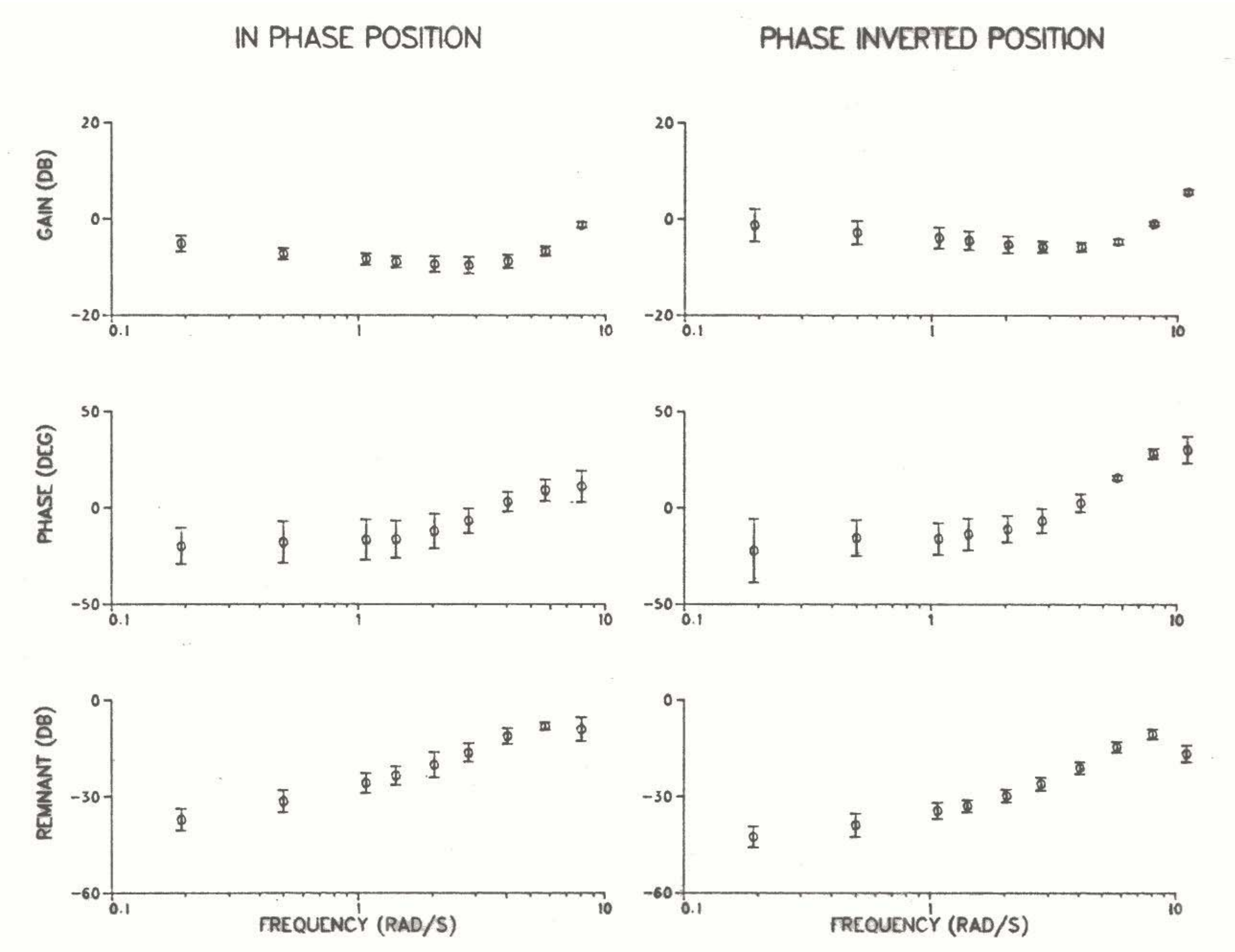

Figure A-17. Asymptotic HODF obtained from the <u>Position "Drive Law" groups</u> during training <u>in the dynamic seat</u>

These subjects were trained for 14 sessions using the following drive laws for the in-phase and phase-inverted groups, respectively :

Seat Roll (degrees) = +0.32 × *Model Roll* (degrees)
Seat Roll (degrees) = –0.32 × *Model Roll* (degrees)

where "model" refers to the analog simulation of the whole-body motion device. The describing functions are averaged across the two subjects in each group over the last two training sessions (eight runs). Mean values, plus/minus one standard deviation, are shown.

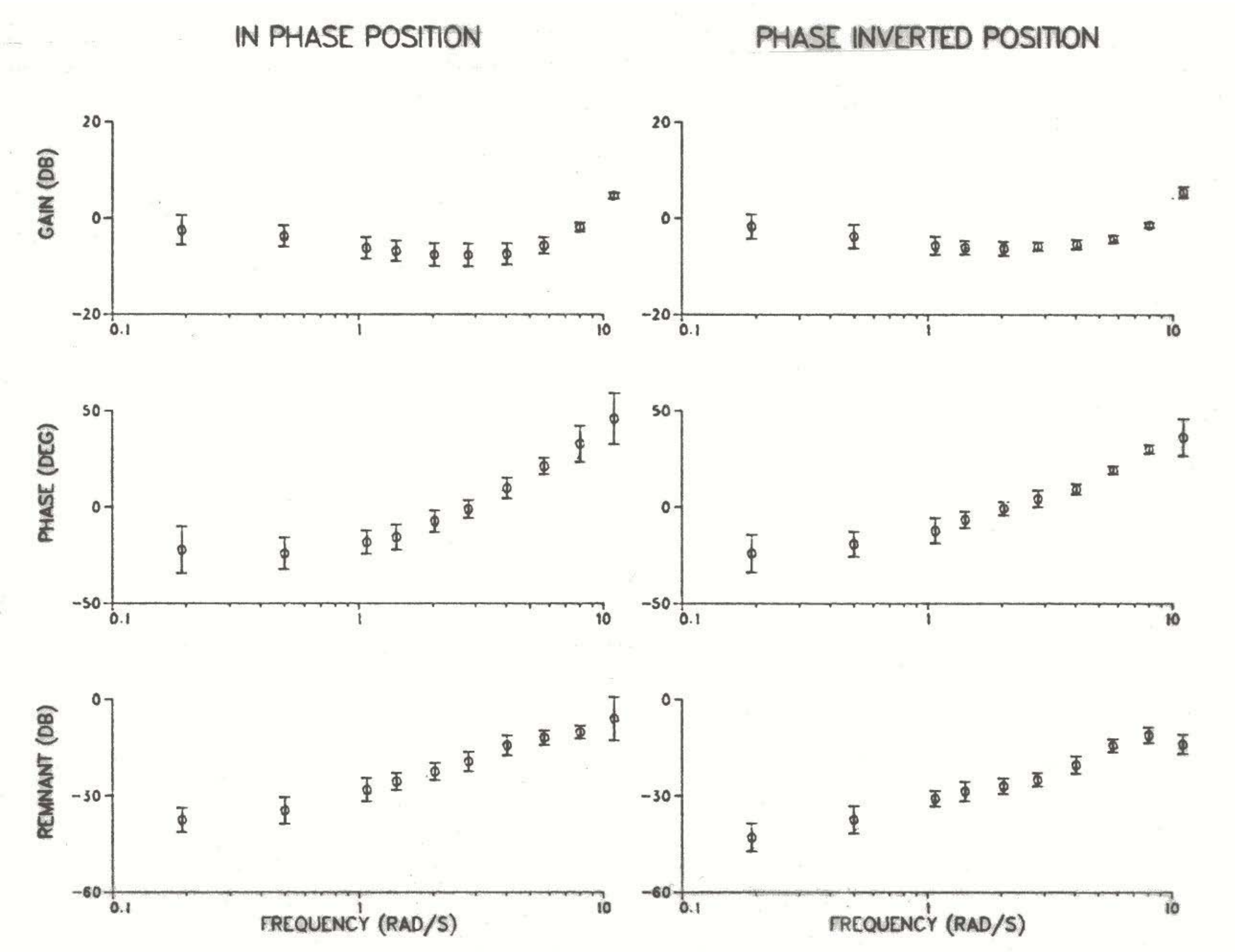

Figure A-18. Asymptotic HODF obtained from the two <u>Position "Drive Law" groups</u> with <u>whole-body motion</u>

These data are averaged across the two subjects in each group over the last two sessions (eight runs) in the full-motion device. Mean values, plus/minus one standard deviation are shown.

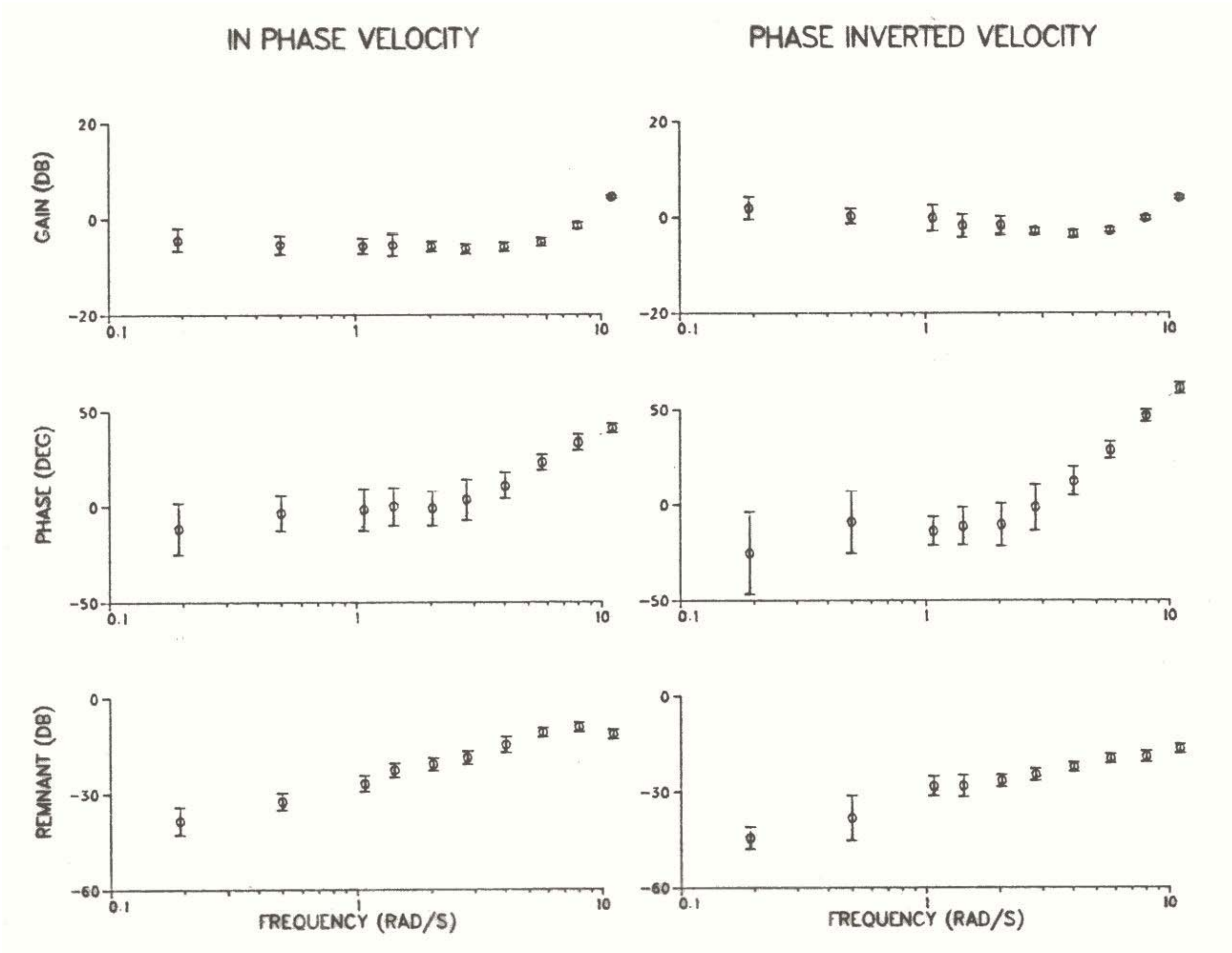

Figure A-19. Asymptotic HODF obtained from the <u>Velocity "Drive Law" groups</u> during training <u>in the dynamic seat</u>

These subjects were trained for 14 sessions using the following drive laws for the in-phase and phase-inverted groups, respectively:

$$\textit{Seat Roll}\ \text{(degrees)} = +0.23 \times \textit{Model Roll Velocity}\ \text{(degrees/s)}$$
$$\textit{Seat Roll}\ \text{(degrees)} = -0.23 \times \textit{Model Roll Velocity}\ \text{(degrees/s)}$$

where "model" refers to the analog simulation of the whole-body motion device. The describing functions are averaged across the two subjects in each group over the last two training sessions (eight runs). Mean values, plus/minus one standard deviation, are shown.

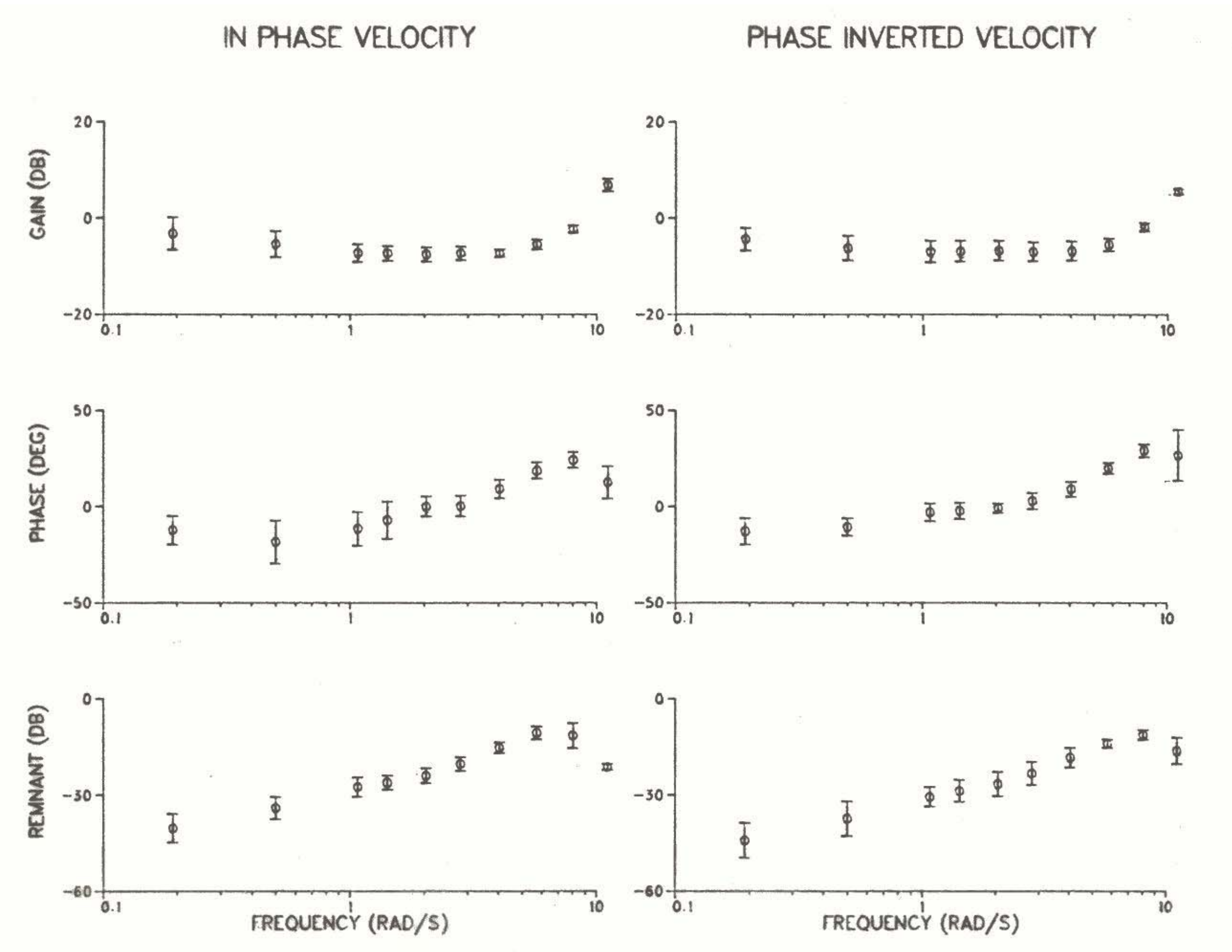

Figure A-20. Asymptotic HODF obtained from the two <u>Velocity "Drive Law" groups</u> with <u>whole-body motion</u>

These data are averaged across the two subjects in each group over the last two sessions (eight runs) in the full-motion device. Mean values, plus/minus one standard deviation are shown.

Table A–4. “Drive Law” ratings based upon observed similarities

Ratings were assigned based upon similarities between the last dynamic seat training run and the first (TRANsfer) and the last (ASYmptotic) full motion runs on the following basis:

1 point if no overlap of the training and full motion standard deviation (SD) bars (i.e., low similarity).
2 points if the SD bars overlap but neither mean is within 1 SD of the other.
3 points if one mean is within 1 SD of the other.
4 points if both means are within 1 SD of each other (i.e., high similarity).

	POSITION DRIVE LAW				VELOCITY DRIVE LAW			
	IN-PHASE		INVERTED		IN-PHASE		INVERTED	
	TRAN	ASY	TRAN	ASY	TRAN	ASY	TRAN	ASY
Tracking Error	4	3	1	4	1	3	1	2
Crossover Freq	4	2	1	4	2	2	1	1
Phase Margin	3	4	1	4	3	4	3	4
Gain	2	2	1	4	1	3	1	2
TOTAL POINTS	13	11	4	16	7	12	6	9
COMBINED RATING	24		20		19		15	

A.9 Three Final Tests—Auditory Cues, Vestibular Cues, and Velocity “Drive Law” Gain

Three issues had arisen during the course of the preceding pilot work which remained to be addressed. The first of these regarded the usefulness of auditory information arising from the operation of the hydraulic seat pan. The second was a concern that there might be useful vestibular information imparted by the motion of the dynamic seat. The third issue arose because of complaints by Velocity “Drive Law” subjects regarding seat motion “violence” early in training; this prompted concern regarding the magnitude of the gain for this “Drive Law,” and the question of interest was whether any significant differences in tracking performance would result if the gain were reduced to a lower level (it appeared that a 50% reduction would reduce seat activity to a reasonable level for a novice tracker).

Short studies were undertaken to address each of the above issues. Subjects still available from the two previous pilot studies were used. Each subject was first provided two refresher sessions in the dynamic seat with his original “Drive Law.” Following this, two sessions (8 runs) of data were collected with the administration of treatment conditions balanced to compensate for order effects.

The first study pertained to the usefulness of seat noise. For this study, subjects were seated on a board fixed above the seat pan such that the seat could be operated normally without providing "seat-of-the-pants" information. Subjects wore the helmet and adjusted the white noise level just as they had during previous training sessions. "Seat noise" runs were provided by driving the seat normally; "no seat noise" runs were provided by simply not driving the seat. Repeated measures were taken on all subjects for both treatment conditions. An appropriate analysis is the Randomized Block Factorial ANOVA (Kirk, 1968). The rms tracking error data and the ANOVA results are provided in Table A–5. As is seen in the tabulated results, differences due to the presence or absence of seat noise are not significant ($F(1,5)=0.21$). The main effect of "blocks", which is seen to be significant ($F(5,35)=37.85$), simply reflects individual differences among the subjects.

In the next study, the usefulness of vestibular information imparted by motion of the dynamic seat was investigated. To test for vestibular effects, subjects were alternated between "head free" and "head stabilized" conditions while tracking with the dynamic seat "Drive Law" with which they were experienced. Head stabilization was accomplished through the use of a bite bar rigidly affixed to the framework of the dynamic seat's enclosure. As before, treatment conditions were randomized for each subject, and balanced to compensate for order effects. Subjects were volunteers drawn from the subject pool used for the prior "seat noise" test. The tracking error data and ANOVA results are provided in Table A–6. As is seen from the ANOVA table, differences in performance, with and without vestibular information (Factor A), are not significant ($F(1,3)=7.22$).

The final study investigated the effect of reducing the gain of the Velocity "Drive Law" by 50%. Velocity "Drive Law" trained subjects were drawn from the "seat noise" test subject pool. A Randomized Block Design was again employed. The tracking error data and ANOVA results are presented in Table A–7. The main effect of "gain" (Factor A) turned out not to be significant ($F(1,2)=16.73$).

Table A–5. Tracking performance with & without seat noise—without seat-of-the-pants cuing

This is a Type RBF-24 Randomized Block Factorial Design. Factor A has two levels of SEAT NOISE (on and off). Factor B has four levels of RUNS. Repeated measures were taken on all subjects for four runs at each level of A. The dependent variable was the rms tracking error tabulated below.

RMS TRACKING ERROR SCORES

	A1 = NO SEAT NOISE				A2 = SEAT NOISE			
	B1	B2	B3	B4	B1	B2	B3	B4
SUBJECT 013	9.10	6.76	7.41	6.12	7.47	6.92	7.15	6.78
SUBJECT 020	5.60	5.43	5.04	5.20	5.71	5.65	5.21	5.23
SUBJECT 021	7.14	6.63	5.93	5.98	6.99	7.68	6.77	6.42
SUBJECT 023	7.93	7.26	6.88	7.00	7.55	8.16	6.73	6.94
SUBJECT 026	5.48	5.36	5.00	5.13	5.33	5.40	5.42	4.93
SUBJECT 026	6.72	6.93	7.00	6.66	6.52	6.94	6.78	6.29
MEANS	7.00	6.40	6.21	6.02	6.60	6.79	6.34	6.10

ANALYSIS OF VARIANCE TABLE FOR TYPE RBF-24 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
BLOCKS	32.11	5	6.42	37.85	**		.76
RESIDUAL	5.94	35	0.17				
A	0.03	1	0.03	0.21	NS	NS	.00
A X BLOCKS	0.83	5	0.17				
B	3.87	3	1.29	5.39	**	NS	.07
B X BLOCKS	3.59	15	0.24				
AB	0.99	3	0.33	3.27	NS	NS	.01
AB X BLOCKS	1.52	15	0.10				
TOTAL	42.94	47					

** $p < 0.05$ F(.05;1,5) = 6.61 F(.05;3,15) = 3.29
NS = Not Significant F(.05;5,35) = 2.49

Table A–6. Tracking performance with head-stabilized vs. head-free

This is a Type RBF-24 Randomized Block Factorial Design. Factor A has two levels of VESTIBULAR INFORMATION ("head stabilized" and "head free"). Factor B has four levels of RUNS. Repeated measures were taken on all subjects for four runs at each level of A. The dependent variable was the rms tracking error tabulated below.

RMS TRACKING ERROR SCORES

	A1 = HEAD STABILIZED				A2 = HEAD FREE			
	B1	B2	B3	B4	B1	B2	B3	B4
SUBJECT 013	2.74	2.65	2.59	2.42	2.57	2.75	2.51	2.50
SUBJECT 020	1.67	1.75	1.52	1.41	1.47	1.37	1.42	1.26
SUBJECT 021	2.28	1.91	1.97	1.81	1.83	1.99	2.11	1.74
SUBJECT 026	2.89	2.61	2.46	2.33	2.60	2.17	2.38	2.57
MEANS	2.40	2.23	2.14	1.99	2.12	2.07	2.11	2.02

ANALYSIS OF VARIANCE TABLE FOR TYPE RBF-24 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
BLOCKS	6.39	3	2.13	124.50	**		.90
RESIDUAL	0.36	21	0.17				
A	0.10	1	0.03	7.22	NS	NS	.01
A X BLOCKS	0.04	3	0.17				
B	0.26	3	1.29	5.27	**	NS	.02
B X BLOCKS	0.15	9	0.24				
AB	0.11	3	0.33	1.92	NS	NS	.01
AB X BLOCKS	0.17	9	0.10				
TOTAL	7.22	31					

** $p < 0.05$ $F(.05;1,3) = 10.13$ $F(.05;3,9) = 3.86$

NS = Not Significant $F(.05;3,21) = 3.07$

Table A–7. Tracking performance for two levels of Velocity "Drive Law" gain

This is a Type RBF-24 Randomized Block Factorial Design. Factor A has two levels of VELOCITY "DRIVE LAW" GAIN (0.115 and 0.23 deg/deg/s). Factor B has four levels of RUNS. Repeated measures were taken on all subjects for four runs at each level of A. The dependent variable was the rms tracking error tabulated below.

RMS TRACKING ERROR SCORES

	A1 = LOW GAIN				A2 = HIGH GAIN			
	B1	B2	B3	B4	B1	B2	B3	B4
SUBJECT 020	1.50	1.52	1.70	1.54	1.36	1.39	1.27	1.48
SUBJECT 023	3.12	2.77	3.08	3.40	2.71	2.81	2.56	2.70
SUBJECT 026	2.41	2.10	2.19	2.05	2.00	1.93	1.96	2.00
MEANS	2.34	2.13	2.32	2.33	2.02	2.04	1.93	2.06

ANALYSIS OF VARIANCE TABLE FOR TYPE RBF-24 DESIGN

SOURCE	SS	DF	MS	F RATIO	CONV	CONS	SOA
BLOCKS	8.16	2	4.08	199.30	**		.93
RESIDUAL	0.29	14	0.02				
A	0.43	1	0.43	16.73	NS	NS	.03
A X BLOCKS	0.05	2	0.03				
B	0.05	3	0.02	1.03	NS	NS	.00
B X BLOCKS	0.09	6	0.02				
AB	0.08	3	0.03	1.05	NS	NS	.00
AB X BLOCKS	0.15	6	0.02				
TOTAL	9.01	23					

** $p < 0.05$ $F(.05;1,2) = 18.51$ $F(.05;3,6) = 4.76$

NS = Not Significant $F(.05;2,14) = 3.74$

A.10 Final Adjustments in the Development of a Position "Drive Law" and a Velocity "Drive Law"

As a result of the relatively weak effect seen for the Velocity "Drive Law" gain differences, it was decided to reduce the gain by about 50% in order to make dynamic seat motion less objectionable for the novice tracker. At the same time it was decided to try to match the cuing dynamic range of the Velocity Drive Law to that of the Position "Drive Law" in terms of the variance of the displayed parameter. To do this the position variance was estimated by pooling the mean-squared tracking error (which is identically mean-squared model position for this task) over the last eight dynamic seat training runs for the three in-phase Position "Drive Law" subjects. The velocity variance was similarly estimated by pooling the mean-squared model velocity over the last eight dynamic seat training runs for the in-phase Velocity "Drive Law" subjects. The standard deviation (SD) for each parameter was then computed by taking the square root of its variance. The SD (or pooled rms) value for position was 3.66 degrees, and for velocity was 9.92 degrees/s. Before proceeding further, a small adjustment was made to the Position "Drive Law" gain (Equ.(A-7)) solely for convenience in reporting its value; this adjustment was a change in gain from 0.32 to 0.33 seat-degrees/model-degrees. With this new gain, the model position range (in SD units) which can be displayed within the 11.12 degrees travel limit of the seat is:

$$\text{Range} = \frac{11.12\ \text{seat-degrees maximum}}{\left(3.66\ \text{model-degrees/SD}\right)\left(0.33\ \text{seat-degrees/model-degrees}\right)}$$

$$\text{Range} = 9.21\ \text{SD} \quad \text{(A-9)}$$

The Velocity Drive Law gain which will result in cues displayed over the same 9.21 SD range within seat travel limits is given by:

$$\text{K} = \frac{11.12\ \text{seat-degrees maximum}}{\left(9.92\ \text{model-degrees/s/SD}\right)\left(9.21\ \text{SD}\right)} = 0.122\,\frac{\text{seat-degrees}}{\text{model-degrees/s}} \quad \text{(A-10)}$$

The value of the Velocity "Drive Law" gain K, thus derived, was only 6% larger than the low gain tested in the "Velocity "Drive Law" gain" test above—a difference which was not expected to make much difference in the "violence" level of the seat. In fact, it was decided to increase the gain another 2%, up to 0.125 seat-degrees/model-degrees/s, for convenience in reporting its value.

As a result of this work, the following dynamic seat "Drive Laws" were derived. Each is a function of its respective model (i.e., analog simulation of the whole-body motion device) parameter.

The Position "Drive Law" is:

$$\text{Seat Roll (degrees)} = \left(\frac{1}{3}\right) \text{Model Roll (degrees)} \quad \text{...(A-11)}$$

The Velocity "Drive Law" is:

$$\text{Seat Roll (degrees)} = \left(\frac{1}{8}\right) \text{Model Velocity (degrees/s)} \quad \text{....................................(A-12)}$$

APPENDIX B

Approximating Lag Dynamics as Pure Time Delays in the Steady-State Frequency Domain

B.1 Background

In developing a hybrid simulation of the sort used in this experiment, it is sometimes convenient to characterize simulator component lag dynamics as pure sinusoidal time delays. Doing this permits one to account for lag dynamics by simple algebraic addition of the equivalent transport delays—thereby avoiding the need to convolve transfer functions in the time domain. This technique also provides a way to consistently account for both analog and digital delays.

The method has been widely used as a technique for accounting for lags beyond the frequency range of immediate interest (e.g., McRuer et al., 1965). Baron et al., (1980) applied this approach to the hybrid simulator problem, describing the procedure in some detail. For the approximation to be valid, it is necessary that the phase lag of the system component be reasonably proportional to frequency, and that the gain be reasonably close to unity over the frequency range of interest. These constraints are not particularly exceptional. In fact, if these conditions are not met, phase and/or gain distortion will be introduced (Geddes and Baker, 1975).

The frequency region of interest for manual control generally includes frequencies up to about 10 rad/s (Baron et al., 1980; McRuer and Jex, 1967; Stapleford et al., 1969). In this experiment, 11 rad/s (corresponding to an input frequency just beyond 10 rad/s) is taken to be the highest frequency of interest.

B.2 Development of the Time Delay Approximation

In the steady state frequency domain, a pure time delay (or transport lag) exhibits unity gain and a phase lag which is directly proportional to frequency at all frequencies (D’Azzo and Houpis, 1966). A low-pass, second-order system mimics these characteristics at frequencies sufficiently below the undamped natural frequency, ω_n, of the system (“sufficiency” depends both on the damping ratio, which affects the quality of the approximation, and on tolerable error—see Fig. B–1). In this experiment, the only simulator components with natural frequencies adequately above 11 rad/s were the Butterworth de-aliasing filters, the “dynamic seat” actuator dynamics, and the filters on the DAC outputs servicing the dynamic seat actuator commands. It happens that these components all exhibited second order dynamics. For this reason the development which follows is limited to second order systems, although the technique can be applied to systems of different order (Baron et al., 1980).

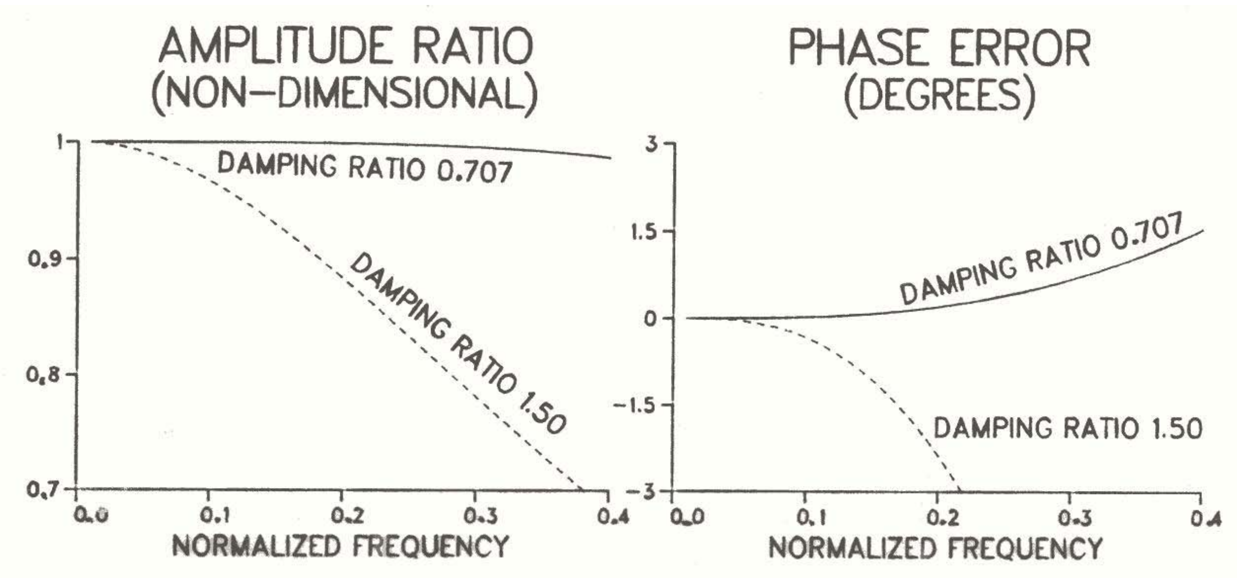

Figure B–1. Amplitude ratio and phase error introduced by approximating second-order lag dynamics as an equivalent sinusoidal transport delay

Data are shown for two different damping ratios, 0.707 and 1.50. The abscissa is scaled in terms of the normalized frequency ratio (ω/ω_n). The AMPLITUDE RATIO shown is the theoretical plot for a unity gain second order system. The PHASE ERROR corresponds to the phase angle value obtained using the time delay approximation of Equ.(B-2) less the true theoretical value calculated from Equ.(B-1). For a true transport delay, the AMPLITUDE RATIO would be unity and the PHASE ERROR zero at all frequencies.

Consider the phase angle of a second order system with natural frequency ω_n and damping ratio ζ, which is given by (D'Azzo and Houpis, 1966):

$$\text{Angle} = -\text{Arctan}\,\frac{2\left(\zeta\right)\left(\dfrac{\omega}{\omega_n}\right)}{1-\left(\dfrac{\omega}{\omega_n}\right)^2} \quad \text{...(B-1)}$$

where ω is the angular frequency in rad/s. If the phase angle is sufficiently small, a small angle approximation for the tangent applies. If, further, $\left(\omega/\omega_n\right)^2$ is small compared to unity, Equ.(B-1) reduces to:

$$\text{Angle} = -\,2\left(\frac{\zeta}{\omega_\text{n}}\right)\left(\omega\right) \quad \text{...(B-2)}$$

Under these conditions, it is seen from Equ.(B-2) that the phase angle varies directly with frequency—with the constant of proportionality τ given below.

$$\tau = 2\left(\frac{\zeta}{\omega_\text{n}}\right) \quad \text{...(B-3)}$$

τ is the effective sinusoidal transport time (in seconds) for the second order lag dynamics.

Table B–1 summarizes the dynamics of the three simulator devices approximated as pure time delays, the effective device sinusoidal time delay τ, and the gain and phase errors at 11 rad/s which result with this approximation.

Table B–1. Approximation of simulator component dynamics as transport lags

Actual system dynamics are second order and shown as [ω_n, ζ], where ω_n is the undamped natural frequency in rad/s and ζ is the dimensionless damping ratio. τ is the effective transport time calculated according to Equ.(B-3). The GAIN ERROR tabulated is the calculated gain of the second order system at 11 rad/s (the gain of a pure time delay would be 0 db at all frequencies). The ANGLE ERROR tabulated is the phase angle value calculated for the time delay approximation using Equ.(B-2), less the phase angle calculated for second order dynamics at 11 rad/s using Equ.(B-1).

			ERROR AT 11 rad/s	
DEVICE	**[ω_n, ζ]**	**τ (ms)**	**GAIN ERROR (db)**	**ANGLE ERROR (degrees)**
Butterworth Filter	[49.6, 0.707]	28.5	–0.010	0.286
DAC Filter	[314., 1.50]	9.6	–0.037	–0.015
Dynamic Seat Actuator	[73.1, 0.707]	19.3	–0.002	0.091

$$\tau \text{ (seconds)} = 2\left(\frac{\zeta}{\omega_n}\right)$$

APPENDIX C

Asymptotic Model Goodness-of-fit Criteria

An asymptotic model of the form

$$y = a + b\left(1 - R\right)^{x},\ 0 < R < 1 \text{ and } x = 0, 1, 2, \ldots \quad \text{...(C-1)}$$

is an exponential decay model representing the relationship between y and x as y tends asymptotically to a limit, a, when x tends to infinity. Stevens (1951) published an algorithm for fitting data to a model of this form, which was later implemented in a BMD Biomedical Computer Program (Dixon, 1973). Stevens provided certain caveats regarding the appropriateness of this model. Namely, he cautioned that if R becomes too small, it is a warning against attempting to fit an asymptotic regression formula; he warned that it is extremely dangerous to attempt to extrapolate for high values of x under these circumstances. He also warned that the rising (or falling) portion of the curve should be adequately defined. Stevens provided a set of criteria regarding the conditions for an acceptable asymptotic model fit which were incorporated into an a priori goodness-of-fit decision rule used in the analysis of data from this experiment.

Stevens' criterion for adequate definition of the rising (or falling) portion of the curve requires that R not be greater than 0.750. It was necessary to extrapolate Stevens' criterion regarding adequate definition of the asymptote since his paper dealt with a maximum of seven values of the independent variable (Stevens was concerned with the arithmetic labor involved, which was a problem before the widespread use of computers). We need to be able to handle up to 80 values. It turned out that Stevens' tabulated limits corresponded to values of R for which the estimate of the dependent variable, y, would—on the average—be within 14% of the estimate for the asymptote, within the scope of the data. Satisfying this criterion requires that R not be less than 0.025 for x=79 (corresponding to 80 training runs). Hence the decision rule for accepting the asymptotic model fit is the following.

> If R is not greater than 0.750, <u>and</u> if R is not less than 0.025, accept the asymptotic regression estimates. Otherwise, the asymptotic model does not appropriately represent the data.

This decision rule was examined against asymptotic fits of preliminary data with good results before being adopted as the criterion to be applied to the experimental data fits. “Goodness” was in terms of what would be judged a reasonable fit, and in terms of control of the standard error of the model parameters (Stevens observed that if the asymptote is not well defined, the standard error of the model parameter estimates begins to diverge sharply to very high values).

APPENDIX D

Facsimiles of Consent Forms and Notes Provided Subjects

D.1 Consent Form for Motion Cuing Study

I,____________________, having full capacity to consent, do hereby volunteer to participate in a research study entitled: "The Influence of G-seat Cue Motion Information on Training and Performance in a Roll Axis Compensatory Tracking Task" under the direction of Mr. Edward Martin, Dr. Grant McMillan, and Ms. Barbara Bachtell. The implications of my voluntary participation, the nature, duration and purpose, the method and means by which it is to be conducted, and the inconveniences and hazards which may be reasonably expected have been explained to me by <u>Edward Martin</u>, and are set forth on the addendum to this agreement, which I have initialed. I have been given the opportunity to ask questions concerning this research project, and any such questions have been answered to my full and complete satisfaction. I understand that I may at any time during the course of this project, revoke my consent, and withdraw from the project without prejudice; however, I may be required to undergo certain further examinations if, in the opinion of the attending physician, such examinations are necessary for my health or well being.

I FULLY UNDERSTAND THAT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. MY SIGNATURE INDICATES THAT I HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

_________(Signature)_________ ___(Date)____ __(Time)__

I was present during the explanation referred to above, as well as the volunteer's opportunity for questions, and hereby witness the signature.

_________(Signature)_________ ___(Date)____

I have briefed the volunteer and answered questions concerning the research project.

_________(Signature)_________ ___(Date)____

D.2 Addendum to the Consent Form

You are invited to participate in an experiment designed to evaluate transfer of training from the Advanced Low Cost G-cuing System (ALCOGS) to the Roll Axis Tracking Simulator (RATS). The ALCOGS and RATS are devices which simulate aircraft movement.

In this experiment you will be asked to perform a compensatory tracking task. The task involves keeping the wings of the aircraft level by moving a control stick in order to null out the presence of the randomly appearing disturbance. All subjects will receive the same visual display and random disturbance. Root mean squared error will be calculated from the angle the wings deviate from the straight dotted reference line.

You will be assigned to a group and will be trained under one of the four following conditions.

Group No.	Training Device	Motion Cuing
I	ALCOGS/RATS	Cab Static
II	ALCOGS	Seat elements active; Position Drive Algorithm
III	ALCOGS	Seat elements active; Velocity Drive Algorithm
IV	RATS	Full Motion Environment

This experiment will include two preliminary familiarization sessions—one to instruct you in a workload scaling technique that we will be using, and a second to familiarize you with the tracking task and motion environment. Following this, there will be a total of 20 sessions of tracking training. Each session will consist of four runs which will each last three minutes. Following training, performance data for all groups will be obtained in the RATS motion environment. There will be 10 sessions of transfer data collected for each subject in the RATS. Workload measures will be collected in all sessions.

We will record your name along with the date at which the experiment is performed, for the purpose of identifying your data, but a numeric code will be used to identify the data in any publication.

D.3 Notes Provided Trackers after the Familiarization Session

Each tracking session will consist of four 3-minute runs. At the beginning of each run, you will be told that the task is being started. You will always be given 15 seconds to stabilize yourself before scoring begins.

Hints for Improving your Tracking Score

1. Remove wallets and other bulky objects from your pockets.

2. The disturbance is truly random. You will not be able to learn this input as you might second-guess video games.

3. Hold the control stick in whatever fashion seems most comfortable. The higher you hold the stick, the more lever arm you will have (i.e., less force will be required for a given roll velocity command, the higher you hold the stick). There is no best position, pick a grip height that is comfortable for you.

4. A relatively light grip on the stick is recommended.

5. Smooth, continuous inputs seem to work best. Try to correct errors before they get too large. Don’t undercontrol—i.e., don’t try to zero your error by sneaking up in small, discrete steps. On the other hand don’t overcontrol—i.e., don’t apply overly large forces on the stick as these will cause you to overshoot. You may find that once you have zeroed the error, a small reverse command is needed to stop rolling.

6. Root mean squared tracking error is scored. This penalizes large errors more severely than small errors.

7. Try to relax. Attend to the task, but don’t tense up. Blink frequently to reduce eyestrain.

APPENDIX E

Selection of the Control Behavior Metrics

Control behavior is appropriately cast in terms of control theory with a functional dependence on frequency (Jex, 1971). This appendix focuses upon the reduction of the frequency domain measures (obtained by Fourier transforming the time history records) into a suitable data set testable for differences in control behavior among experimental groups. A constraint was imposed that the data reduction process be readily automated. This was done for two reasons: (1) automation was necessary in order to keep the process manageable with the large number of experimental runs involved, and (2) it was desired to avoid the introduction of any subjective bias potentially arising from manual data fits.

A number of researchers have shown that motion information is used by human operators performing tracking tasks similar to that used in this experiment to modify their control behavior (e.g., Levison and Junker, 1977; Shirley, 1968; Stapleford et al., 1969). McRuer et al., (1965) note that individual differences in tracking style are tightly constrained in the vicinity of crossover. It turns out that under certain key assumptions (summarized by Jex, 1971) which were satisfied by the conditions of this experiment, McRuer's Crossover Law of Operator Control Behavior captures the effects of changes in operator equalization resulting from the different motion conditions. This permitted the efficient approximation of the operator's control behavior in terms of a (modified) "simple crossover model" (McRuer and Jex, 1967; Jex, 1971). Attention was limited to the immediate region of crossover in order that the effects of individual differences due to tracking style would be minimized; therefore an extension of the model to account for "low frequency phase droop" was not needed. Loop gain, crossover frequency, and amplitude ratio slope were all retained as model parameters in order to avoid the unnecessary imposition of structure on the data. Within this context, the magnitude and phase of the crossover model took on the following respective forms.

$$\left|HV(j\omega)\right| = \frac{K_L}{\omega^N} \quad \text{(E-1)}$$

$$\underline{/HV(j\omega)} = -(N)\,(90 \text{ degrees}) - (\omega)\,(\tau_E)\,(57.3 \text{ degrees/rad}) \quad \text{(E-2)}$$

where ω is in rad/s, K_L is the open loop amplitude ratio (gain), N is a non-dimensional gain slope parameter (normally having a value close to unity—corresponding to 20 db/decade), and τ_E is an effective time delay (in seconds) lumping the cumulative perceptual-motor delays and higher-frequency lags. The open loop phase angle $\underline{/HV(j\omega)}$ is expressed in units of degrees, consistent with the data presented in the body of the report.

τ_E can be expressed in terms of the crossover frequency, ω_C, and phase margin, φ_M. The phase angle at crossover is first written in terms of the phase margin.

$$\underline{/HV(j\omega_C)} = \varphi_M - 180 \text{ degrees} \qquad \text{(E-3)}$$

Equating Equ.(E-2) and Equ.(E-3) and solving for τ_E results in:

$$\tau_E = \frac{\left[\left(1 - \frac{N}{2}\right)(180 \text{ degrees})\right] - \phi_M}{\omega_C \,(57.3 \text{ degrees/rad})} \qquad \text{(E-4)}$$

where ω_C is in rad/s, φ_M is in degrees, N is non-dimensional, and τ_E is in seconds. From Equ.(E-4) it is seen that if τ_E is used as the dependent variable, information may be lost regarding independent variations in ω_C, φ_M, and N with different treatment conditions. On the other hand, if ω_C, φ_M, and N are known, τ_E can be recovered. Therefore, ω_C, φ_M, and N, rather than τ_E, were used as dependent variables.

In all, four crossover variables (ω_C, φ_M, K_L, and gain rolloff) were selected to characterize the operators' control behavior. Techniques used to estimate these variables are covered in Section 3.5.